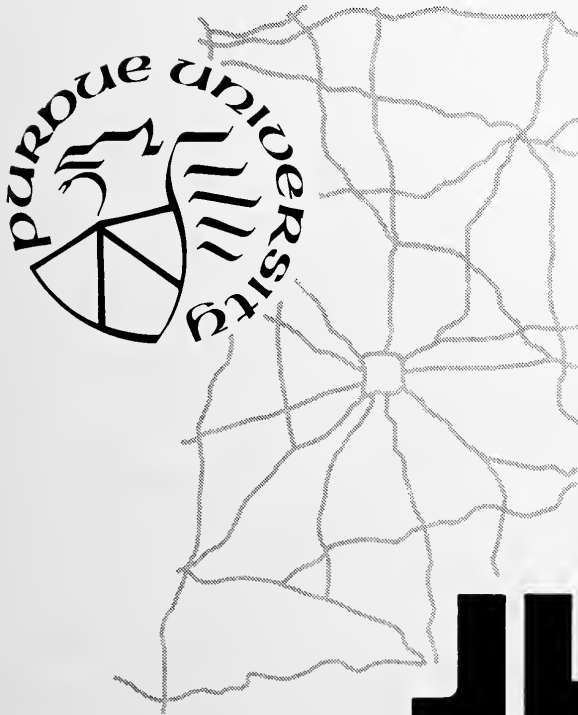


AN INVESTIGATION OF THE USE OF THE MOISTURE -
TENSION METHOD FOR DETERMINATION OF LIQUID
AND PLASTIC LIMIT VALUES OF SOIL

JULY 1972 - NUMBER 15

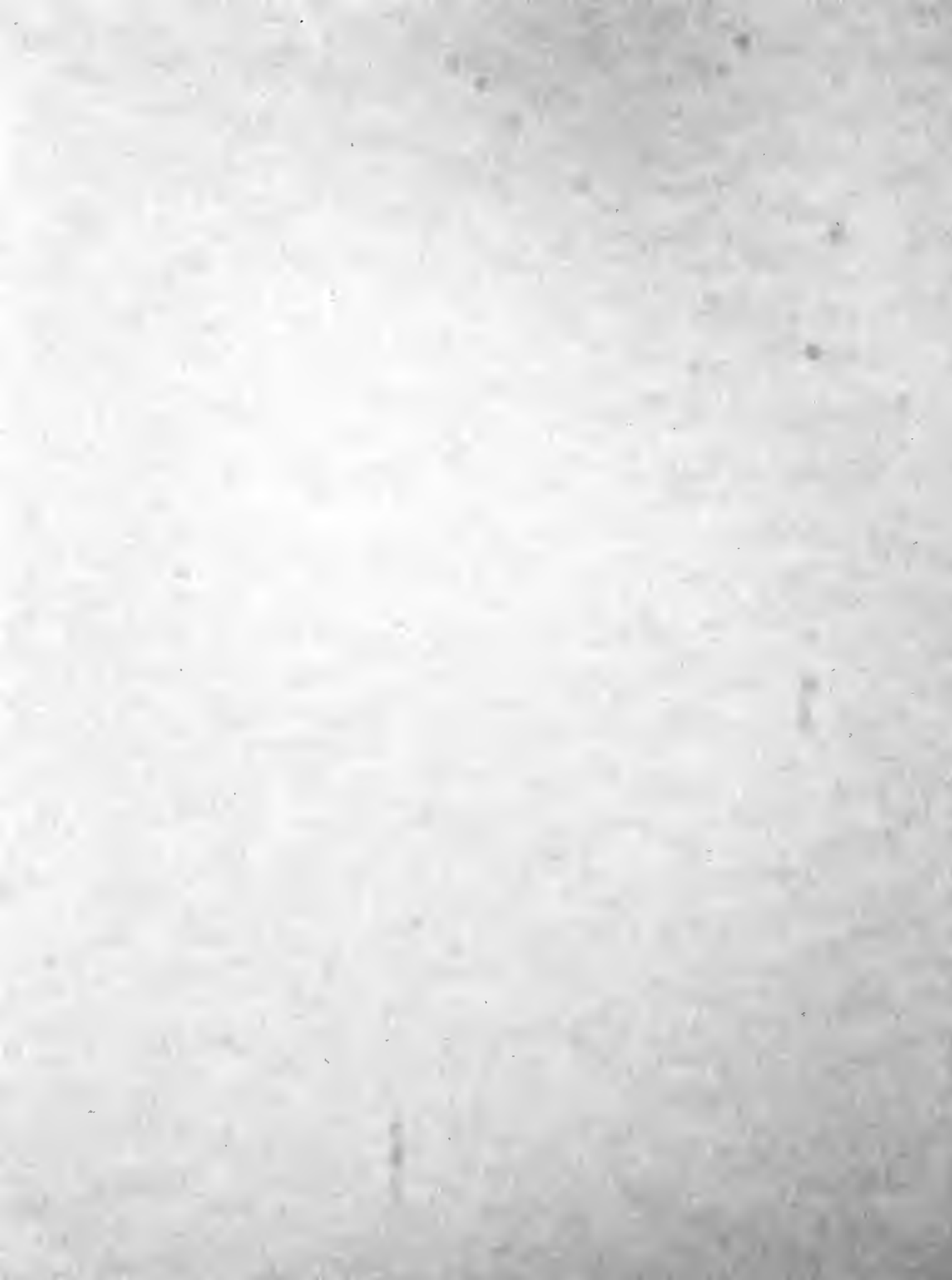


BY

TAKAHIKO NISHIO

JHRP

JOINT HIGHWAY RESEARCH PROJECT
PURDUE UNIVERSITY AND
INDIANA STATE HIGHWAY COMMISSION



Final Report

AN INVESTIGATION OF THE USE OF THE MOISTURE-TENSION METHOD FOR DETERMINATION OF LIQUID AND PLASTIC LIMIT VALUES OF SOIL

TO: J. F. McLaughlin, Director July 26, 1972
Joint Highway Research Project Project: C-36-51

FROM: H. L. Michael, Associate Director File: 6-6-9
Joint Highway Research Project

Attached is a Final Report entitled "An Investigation of the Use of the Moisture Tension Method for Determination of Liquid and Plastic Limit Values of Soil", by Mr. Takahiko Nishio. This work was conducted under the supervision of Professor E. J. Yoder and Mr. Eugene R. Russell of our staff.

The purpose of the study was to investigate the feasibility of using moisture tension techniques for estimating the liquid and plastic limits of soils. If the moisture tension method can be developed so that it will give reliable data it would result in considerable savings in time and money for performing these routine tests.

The results indicate that, using the two moisture-tension devices in our laboratory, the liquid and plastic limits can be predicted with some certainty by this method. Regression equations are presented which relate the consistency limits to moisture content determined using moisture tension techniques.

However, it is believed that additional work should be done to study the method further. The moisture tension method for estimating plasticity is perhaps at the same stage in development as nuclear moisture-density measurement was some 10 years ago. It is our belief that the method can be developed to where it can be used on a production basis by the Indiana State Highway Commission.

The report is submitted for acceptance as fulfillment of the objectives of this Study.

Respectfully submitted,

Harold L. Michael
Harold L. Michael, Associate Director

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Final Report

AN INVESTIGATION OF THE USE OF THE MOISTURE-TENSION
METHOD FOR DETERMINATION OF LIQUID AND PLASTIC LIMIT
VALUES OF SOIL

by

Takahiko Nishio
Graduate Assistant in Research

Joint Highway Research Project

Project No.: C-36-5I

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Conducted By

Joint Highway Research Project
Engineering Experiment Station
Purdue University

In Cooperation With
Indiana State Highway Commission

Purdue University
Lafayette, Indiana
July 26, 1972

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TABLE OF CONTENTS

	Page
LIST OF TABLES.	v
LIST OF FIGURES	vii
ABSTRACT.	ix
INTRODUCTION.	1
PURPOSE OF THE STUDY.	3
REVIEW OF LITERATURE.	4
Research on the Atterberg Limits.	4
Development of Moisture Tension Method.	5
THE APPARATUS AND MATERIAL USED	10
Moisture Tension Method Equipment	10
Extractor and Ceramic Plate Cells	10
Pressure Regulator and Measurement.	12
Other Tools for the Pressure Test	12
Soils and Soil Mixtures	12
PROCEDURES AND TESTS CONDUCTED.	21
Standard Test for Consistency Limits of Soils	21
Moisture Tension Test	21
Preparation	21
Application of Pressure	22
Tests for Moisture Tension Curves	22
Tests for Time Factor Study	23
Tests for Prediction Curves of Atterberg Limits	24
RESULTS	25
Consistency Limits by the Standard Method	25
Prediction of the Plasticity of Soils by the Moisture Tension Method.	33
All Random Combinations	35
Random Pull	36
Analysis of the Artificially Prepared Soils	37
Interpretation of the Regression Analysis Results	37
Prediction of Non-Plasticity by WC_3 and WC_{20}	43

Page

Some Characteristics of the Moisture Tension Method . . . . .	.43
Shape of Moisture Tension Curves. . . . .	.43
The Relationship Between Soil Composition and Moisture Tension. . .	.45
Factors Affecting the Moisture Tension Method . . . . .	.50
Equipment and Ceramic Plate . . . . .	.50
Time Factor Study . . . . .	.52
SUMMARY AND RECOMMENDATIONS . . . . .	.56
BIBLIOGRAPHY. . . . .	.58
APPENDICES	
Appendix A: Test Data. . . . .	.60
Appendix B: Tests for Operator Effect. . . . .	.79
Appendix C: Input Data for Regression Analysis . . . . .	.82
Appendix D: Coefficient of Variation . . . . .	.87
Appendix E: Moisture Tension Curves. . . . .	.90
Appendix F: Relationships Between Moisture Tension and Soil Composition . . . . .	.99

LIST OF TABLES

Table	Page
1. Soil Moisture Tension Giving Moisture Content Approximately the Liquid Limits	7
2. Sieve Analysis of the Natural Soils	15
3. Textural Classification of the Natural Soils.	16
4. Textural Classification of the Artificially Prepared Soils. . .	17
5. Number of Tests Conducted on Natural Soils.	26
6. Liquid Limit Values by Several Operators.	27
7. Plastic Limit Values by Several Operators	29
8. Tests for Operator Effect (LL).	31
9. Tests for Operator Effect (PL).	31
10. Two-way ANOVA of WC_3 and WC_{20} by Three Operators.	34
11. Homogeneity of Variance Calculated for the Data Shown in Table C-1 by the Foster-Burr Test	36
12. Prediction Equations for Consistency Limits (natural soils) .	38
13. Prediction Equations for Consistency Limits (artificially prepared soils)	39
14. Prediction Equations for Consistency Limits (Utah Soils from Sultan).	40
Appendix	
Table	
A-1 Summary of Liquid Limit Values.	60
A-2 Summary of Plastic Limit Values	63
A-3 Summary of Test Results for the Artificially Prepared Soils .	66
A-4 Water Content by Moisture Tension Test (WC_3 , Operator H). . .	67
A-5 Water Content by Moisture Tension Test (WC_{20} , Operator H) . .	68

Appendix
Table

Page

A-6	Water Content by Moisture Tension Test (WC_3 , Operator I) . . .	.69
A-7	Water Content by Moisture Tension Test (WC_{20} , Operator I) . .	.70
A-8	Water Content by Moisture Tension Test (WC_3 , Operator J) . . .	.71
A-9	Water Content by Moisture Tension Test (WC_{20} , Operator J) . .	.72
A-10	Effect of Plate on Test Results . . . . .	.73
A-11	Effect of Time and Pressure on Water Content. . . . .	.74
B-1	Two-way ANOVA for LL. . . . .	.79
B-2	Two-way ANOVA for PL. . . . .	.80
B-3	Tests Between Two Operators, LL . . . . .	.81
B-4	Tests Between Two Operators, PL . . . . .	.81
C-1	Input Data for the all Random Combination Analysis. . . . .	.82
C-2	Input Data for the Random Pull Analysis . . . . .	.86
D-1	Coefficient of Variation, $\frac{S}{D} \times 100$ (%) (LL, PL, WC_3 , WC_{20}) . .	.87
D-2	Coefficient of Variation, $\frac{S}{D} \times 100$ (%) (Predicted LL Values) .	.88
D-3	Coefficient of Variation, $\frac{S}{D} \times 100$ (%) (Predicted PL Values) .	.89
F-1	Soil Composition for the Passing #40 Portion of the Test Soils. . . . .	.99

LIST OF FIGURES

Figure	Page
1. The Extractor and the Ceramic Plate Cell . . . . .	.11
2. Set up of Equipment Showing Two Extractors . . . . .	.13
3. Moisture Tension Test Equipment. . . . .	.14
4. Textural Classification of the Natural Soils . . . . .	.19
5. Textural Classification of the Artificially Prepared Soils . .	.20
6. Suggested Boundary Lines - Non Plastic Soils . . . . .	.44
7. Relationship Between WC_3 and WC_{20} (natural soils). . . . .	.47
8. Relationship Between WC_3 and WC_{20} (artificially prepared soils) . . . . .	.48
9. Relationship Between WC_3 and WC_{20}. . . . .	.49
10. Water Content Variation Between Plates . . . . .	.51
11. The Changes of Water Content Deviation by Pressures. . . . .	.51
12. Effect of Time and Pressure on Moisture Content, Soil No. 2. .	.53
13. Effect of Time and Pressure on Moisture Content, Soil No. 3. .	.53
14. Effect of Time and Pressure on Moisture Content, Soil No. 5. .	.54
15. Effect of Time and Pressure on Moisture Content, Soil No. 6. .	.54
16. Effect of Pressure and Loading Time on Equilibrium Moisture Content . . . . .	.55
Appendix	
Figure	
A-1 Effect of Percent Soil in the Mix on Test Values for the Artificially Prepared Soils. . . . .	.76
A-2 Effect of Percent Soil in the Mix on Test Values for the Artificially Prepared Soils. . . . .	.77

Appendix
Figure

Page

A-3	Effect of Percent Soil in the Mix on Test Values for the Artificially Prepared Soils. . . . .	.78
E-1	Moisture Tension Curves Developed Using Two Procedures for Applying Pressure. . . . .	.90
E-2	Moisture Tension Curves Developed Using Two Procedures for Applying Pressure. . . . .	.91
E-3	Moisture Tension Curves for Three Clays. . . . .	.92
E-4	Moisture Tension Curves for Two Clay Loams (1) . . . . .	.93
E-5	Moisture Tension Curves for Two Clay Loams (2) . . . . .	.94
E-6	Moisture Tension Curves for Two Sandy Clay Loams (1) . . . . .	.95
E-7	Moisture Tension Curves for Three Sandy Clay Loams (2) . . . . .	.96
E-8	Moisture Tension Curve for Loam. . . . .	.97
E-9	Moisture Tension Curve for Sandy Loam. . . . .	.97
E-10	Moisture Tension Curve for Silty Clay Loam . . . . .	.98
F-1	Relationship Between the Portion $\#40 \sim 0.05\text{mm}$ and WC_3	101
F-2	Relationship Between the Portion ($\#40 \sim 0.05\text{mm}$ and -0.005mm) and WC_3	102
F-3	Relationship Between the Portion ($2\text{mm} \sim 0.05\text{mm}$) and WC_3	103
F-4	Relationship Between the Portion (-0.005mm) and WC_{20}	104
F-5	Relationship Between the Portion ($\#40 \sim 0.05\text{mm}$ and -0.005mm) and WC_{20}	105
F-6	Relationship Between the Portion ($-0.05\text{mm} \sim 0.005\text{mm}$) and WC_{20}	106
F-7	Relationship Between the Portion ($\#40 \sim 0.05\text{mm}$) and $(WC_3 - WC_{20})$	107
F-8	Relationship Between the Portion ($-0.05\text{mm} \sim 0.005\text{mm}$ and -0.005mm) and $(WC_3 - WC_{20})$	108

ABSTRACT

Nishio, Takahiko. M.S.C.E., Purdue University, June 1972. An Investigation of the Use of the Moisture-Tension Method for Determination of Liquid and Plastic Limit Values of Soil. Major Professor: E. J. Yoder.

The purpose of this research was to study the relationship between moisture content as determined by moisture tension techniques and the consistency limits for Indiana soils.

Twenty-eight soils obtained from different locations of the state of Indiana and twenty-nine artificially prepared soils (varying gradations) from the same natural soils were studied. The ceramic plate apparatus was used for the moisture tension method. The effect of using different operators to run both the standard tests for liquid and plastic limit and the moisture tension tests was evaluated.

It was found that either $(WC_{20})^2$, $(WC_3)^2$ or $(WC_3)(WC_{20})$, where WC_3 is moisture content at 3 psi in the moisture tension device and WC_{20} is moisture content at 20 psi correlated well with the liquid and plastic limits and the plasticity index of the soils. The correlation was established for all the soils used regardless of their textural classification. The results of the study suggest the possibility of using moisture tension to estimate the grain size distribution of soils.

INTRODUCTION

Since Albert Atterberg (3) studied the arbitrary identification limits called the "liquid" and "plastic" limits of a soil, a great volume of information has been collected correlating the limits with other soil properties. Some researchers claim that the consistency limits are too empirical and there is no rational basis for them. It is also believed by some that the results are too sensitive subject to variation because of the standard device and because of operator technique.

Recently, however, there have been attempts made by researchers and engineers in this field, to develop new devices and techniques that can be substituted for the present standard method. Hence, it becomes necessary to correlate results by the new methods with those obtained by the standard method, since the results of the standard method have been widely used for such a long period of time.

The moisture tension method has recently been developed and the results used to predict the liquid and plastic limits of a soil (12,13,14). All investigators to date have emphasized that further research is needed. They report some advantages of the new method as follows:

1. It appears possible for a single operator to determine the liquid limit of several hundred soils in a few days.
2. Minimum attention to technique is required and no prior training or experience is necessary to determine values by the method.

3. The results by this method show a higher degree of reproducibility and consistency.

However, all correlations have depended upon grouping the samples into different soil textural classifications. This appears to be one of the shortcomings of the new method, because a partial hydrometer test is necessary to classify the soils. The hydrometer test is time consuming and difficult to run. Another shortcoming is that different pressure intensities are required for various soils depending upon the soil's textural classification. Moreover, very few tests have been made on non-plastic materials. This may be fatal in use of the moisture tension method, since we have a risk of estimating a certain value as a plastic limit of a soil even if it does not actually have a plastic limit in the standard test.

PURPOSE OF THE STUDY

This research project was undertaken to evaluate the feasibility and reliability of using the moisture tension method for predicting the liquid and plastic limits. The specified objectives of this study are as follows:

1. To verify the relationship between the consistency limits and the moisture tension values for various types of soils from the state of Indiana.
2. To establish the above relationship with less restrictions of test technique and regardless of soil textural classification.
3. To investigate equipment and operator variability and reliability of this method.
4. To find if a relationship exists between the soil composition and soil moisture tension values.

REVIEW OF LITERATURE

Research on the Atterberg Limits

The concept of soil plasticity and a method to determine it were first suggested by Albert Atterberg in 1911 (3). Atterberg established the "roll out limit" of a clay; the roll out limit is the moisture content at which the clay paste cannot be rolled into threads. Also, he established the "flow limit" which is the moisture content at which two small portions of clay, lying in a dish, will no longer flow together with vigorous blows of the dish. To Atterberg, plasticity meant "capable of being shaped".

Procedures for determining the plasticity of soil have been greatly refined over the past sixty years. Most researchers have spent major efforts on the improvement of the device and the methods for determining the flow limit. As for roll out limit, the only major improvement has been the specific provision of the diameter of threads (1/8"). The flow limit suggested by Atterberg is now designated as the liquid limit and the roll out limit is known as the plastic limit. These test methods and devices are now specified in ASTM Method D423-61T (1) and D424-59 (2) respectively.

Terzaghi (16) and Casagrande (5) emphasized the necessity for establishing a clear definition for the properties studied by Atterberg. They also raised questions relative to what the test results mean and what factors determine their results. It is known

that even the present test methods as specified in the ASTM are very sensitive to operator technique.

Dawson (6) studied the reliability of liquid limit test results. According to his study, the overall variation in the results ranged from $\pm 5\%$ to $\pm 10\%$; he concluded that the liquid limit test (ASTM Method D423-59T) was questionable and needed further study.

Several questions about the concepts believed and the procedure for determining plasticity of a soil remain unanswered. However, the Atterberg limits have become one of the most important properties of soils and now are widely used. Many studies have been made linking these limits with other properties of soils. Most recent research in the area of the liquid and plastic limits has been directed at making changes in the present devices and methods.

Development of Moisture Tension Method

Richards(8,9,10,11) developed a moisture tension apparatus to measure the capillary potential of soils in 1928. Baver (4) presented a comprehensive explanation of the mechanics of the soil-moisture system. Russell and Mickle (13) summarized Baver's concepts as follows:

"Capillary water is defined as the water which is held by surface forces as a continuous film around the particles and in the capillary spaces. Capillary potential defined as the work required to pull a unit mass of water away from a unit mass of a soil. Thus, when a pressure difference (suction or pressure) is required to extract water from soil, the amount of water in the soil is a function of the energy with which the water is held. Also, the energy required to remove water is a continuous function of the moisture content; i.e., a given energy will remove a given amount of water and come to equilibrium. When the equilibrium condition of the soil has been reached, the soil has a potential at that point equivalent to the suction (or pressure) applied."

The application of the moisture tension test for determining the consistency limits of soils was investigated by Rollins and Davidson (12). They found that moisture content at a specific moisture tension corresponded to the consistency limits of a soil. According to their study, different moisture tension values were evaluated to estimate the consistency limits of soils depending upon the textural classification of the soil. This approach seems reasonable since the size of the soil particles is one of the major factors that has a large effect on moisture tension values.

Sultan (14) and Russell and Mickle (13) continued the studies of Rollins and Davidson. Their procedures for estimating the consistency limits of soils were also based upon soil textural classification.

Sultan used fifty five Utah soils which were classified into five groups of sand, sandy loam, silty loam, loam and silty clay loam. He reported that the liquid limits of these soils could be estimated by the moisture tension method by applying specific pressures to each soil type.

Russell and Mickle (13) conducted their researches on Iowa soils. Basically the same techniques and procedures were used as those adapted by the previous two researchers. The results of Russell and Mickle are shown in Table 1 along with the results of Sultan and Rollins and Davidson.

Table 1. Soil Moisture Tensions Giving Moisture Content Approximately the Liquid Limits

Test Results Textural Classification	Soil Moisture Tension Values, in inches of water (psi)		
	IOWA SOILS		UTAH SOILS
	Russell & Mickle's Data	Rollins & Davidson's Data	Sultan's Data
Clay	40 (1.5)	6 (0.2)	---
Silty Clay	40 (1.5)	15 (0.5)	---
Silty Clay Loam	60 (2.2)	60 (2.2)	120 (4.3)
Loam	70 (2.5)	--	110 (4.0)
Sandy Loam	70 (2.5)	--	65 (2.4)
Silty Loam	--	60 (2.2)	120 (4.3)

It can be concluded from the above researchers that:

1. If the textural classification of a soil is known, its liquid limit can be estimated by assuming it equal to the moisture content obtained at a certain soil moisture tension.
2. The moisture tension method can be used to estimate the liquid limits of soils with less variation due to operator technique than by the ASTM standard method.
3. The quality of the results and the speed of making determinations make the moisture tension method a valuable substitute for liquid limit devices.

However, Sultan (15) compared the results of the three studies. He concluded that the usage of textural classification, or gradation, of the material as the governing factor in selecting the moisture tension values at which to determine the liquid limit did not constitute a conclusive criterion at the current stage of knowledge. As for plastic limits, an insufficient number of tests were conducted to warrant any conclusions in these three research projects.

It can be concluded that there appears to be a good relationship between moisture content determined by moisture tension and the liquid limits of soils and that this method might offer a substitute for the standard consistency tests.

Uppal (17) studied the application of the moisture tension method for evaluating the plastic limit. He concluded that, for soils compacted to a bulk density of 1.6 g/cm^3 , the plastic limit corresponded to the moisture content at pF 0.5 (31.6 cm of water height) by the wetting method or pF 1.5 (31.6 cm of water height) by the drying method. The wetting method is one for which the soil mass is allowed to absorb moisture under a certain pressure and drying method is the one whereby a saturated soil is subjected to a certain suction until it attains equilibrium.

If the air voids can be fixed by controlling the dry bulk density of the soil mass then according to Uppal (17) the plastic limit would only be affected by the amount of solid and liquid in the soil mass. He suggested that a dry bulk density of 1.6 g/cm^3 would give the best results.

The idea that controlling the dry bulk density as an initial condition is interesting. However such a provision of an initial condition makes the test more difficult to perform.

Another study was conducted by Livneh (7). He concluded that in the range of 2 to 4.2 pF (approximately 1.4 psi and 230 psi respectively), a linear correlation was found between the logarithm of moisture content ($\log W$) of a soil and the corresponding suction value (pF). Another linear correlation was found between $\log PI$ of a soil and the corresponding suction value (pF). The main advantage of his method is

that both plastic limit and plasticity index can be estimated by using a given intensity of pressure. However his method also depended upon soil classification.

THE APPARATUS AND MATERIAL USED

Moisture Tension Method Equipment

Extractor and Ceramic Plate Cells

The extractor and the ceramic plate cells are the main apparatus used for the pressure tests of moisture extraction from soils (see Figure 1).

Soil samples are placed on the surface of the ceramic plates and these plates are mounted in the extractor. When pressure is applied in the extractor, excess water from the soil samples is forced out of the extractor through the ceramic plate cells and the outflow tubes.

The extractor has three outlet ports spaced down the wall of the vessel. Each output port takes the outflow from one ceramic plate. A maximum of three ceramic plates can be used in the extractor. Two other ports were used, one for applying pressure to the extractor and the other for measuring this applied pressure by means of a manometer. The outflow tubes from the ceramic plates are connected with the outlet ports on the wall of the extractor to remove the excess water out of the extractor.

Each ceramic plate cell consists of a 1 bar ceramic plate approximately 10 1/4" in diameter which is sealed on one side by a thin neoprene diaphragm. An internal screen keeps the diaphragm from coming into close contact with the plate and provides a passage for flow of water. An outlet stem running through the ceramic plate connects this passage to the outflow assembly.

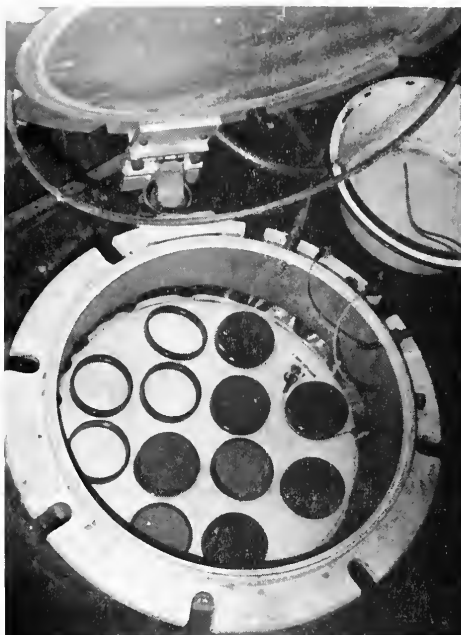


FIGURE 1. THE EXTRACTOR AND THE CERAMIC PLATE CELL

The ceramic plate cells used in this research are designated "1 bar ceramic plate cells". These plates are capable of measurement within a 0 to 1 bar pressure range. A maximum of twelve soil samples can be placed on each plate. Figure 2 shows two extractors as used in this research.

Pressure Regulator and Measurement

Figure 3 shows in diagram form the laboratory set up and illustrates the various operating parts. The inlet air pressure is adjusted to the required intensity by two regulators. One of the regulators is for high pressure and the other is for low pressure. In this research, the range of the pressure applied was 0.4 psi to about 50 psi.

The pressure was measured using two procedures, one was by a test gauge mounted in the regulator system and the other was by a mercury manometer. The manometer was used for low pressure tests up to 10 psi; it was connected directly to the extractor.

Other Tools for the Pressure Test

Rubber rings 1/2" high and 2" in diameter were used for retaining the soil samples on the ceramic plate as illustrated in Figure 1. Glass jars 2" diameter and 6" high were used for saturating soil samples.

Soils and Soil Mixtures

Grain size data and textural classification of the soils are shown in Tables 2, 3 and 4. The textural classification of these soil samples was obtained using the classification system of U.S.

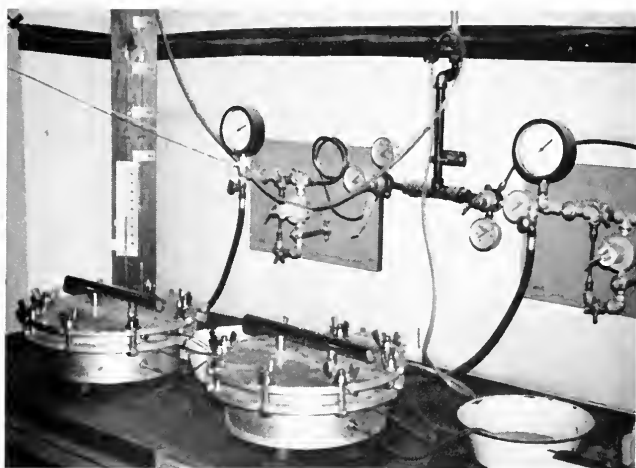


FIGURE 2. SET UP OF EQUIPMENT SHOWING TWO EXTRACTORS

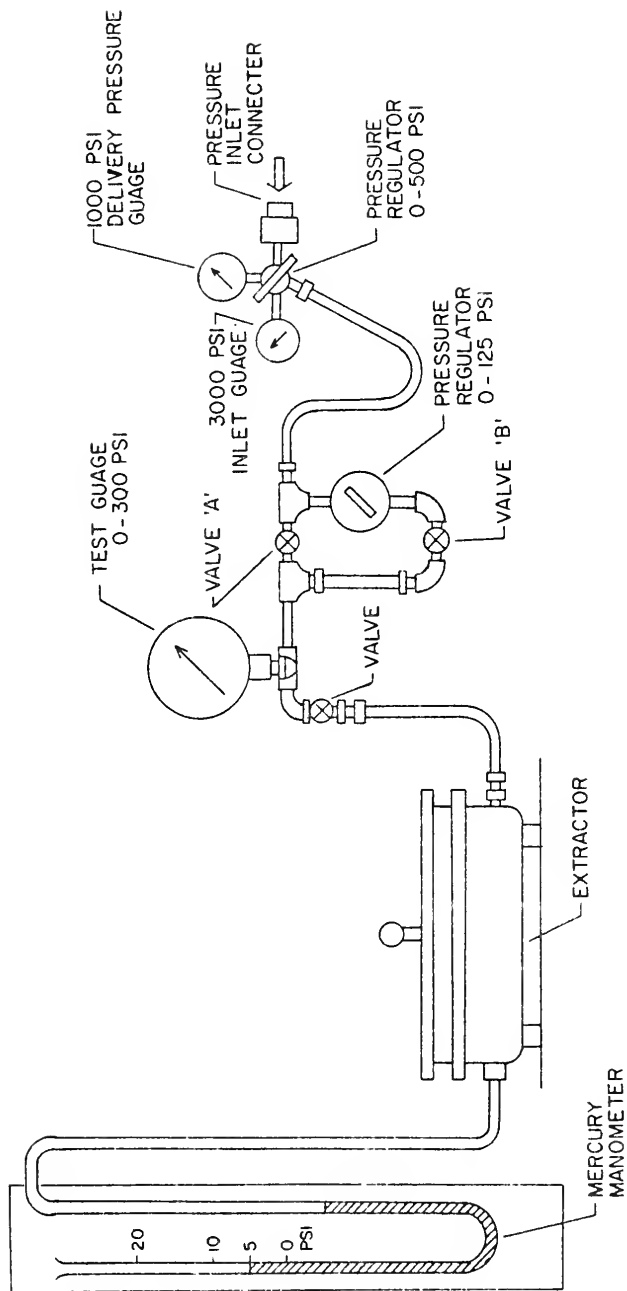


FIGURE 3 MOISTURE TENSION TEST EQUIPMENT

Table 2. Sieve Analysis of the Natural Soils

Soil No.	Percent Passing Sieve or Size				
	#40	#100	#200	0.05 ^{mm}	0.005 ^{mm}
1	99	98	97	97	50
2	99	98	96	92	46
3	97	94	88	84	39
4	96	67	59	58	37
5	96	73	61	58	35
6	81	56	51	51	31
7	83	53	45	44	35
8	84	55	46	44	33
9	93	87	83	80	24
10	91	74	68	65	21
11	75	62	52	48	23
12	84	75	60	49	22
13	90	63	56	51	22
14	92	62	53	50	19
15	77	53	47	44	26
16	98	60	52	48	21
17	81	56	46	43	32
18	80	54	42	38	24
19	91	42	29	26	24
20	96	50	36	33	14
21	90	44	24	24	18
22	40	25	25	25	17
23	100	35	20	18	16
24	95	32	13	12	11
25	40	13	9	9	8
26	45	15	13	12	9
27	93	40	18	16	15

Table 3. Textural Classification of the Natural Soils

Soil No.	Sand $2.0\sim 0.05^{\text{mm}}$ (%)	Silt $0.05\sim 0.005^{\text{mm}}$ (%)	Clay $<0.005^{\text{mm}}$ (%)	Textural Group
1	8	42	50	Clay
2	8	46	46	
3	15	46	39	
4	43	21	36	
5	42	23	35	
6	46	21	33	
7	54	10	36	
8	54	11	35	
9	20	56	24	Silty Clay Loam
10	33	45	22	Clay Loam
11	48	26	26	
12	47	29	24	
13	48	30	22	
14	49	32	19	Loam
15	52	20	28	Sandy Clay Loam
16	53	26	21	
17	54	17	29	
18	60	14	26	
19	74	3	23	
20	67	19	14	Sandy Loam
21	76	6	18	
22	75	8	17	
23	81	2	17	Sand
24	88	1	11	
25	88	1	11	
26	88	3	9	
27	84	1	15	
28	--	--	--	Unclassified

Table 4. Textural Classification of the Artificially Prepared Soils

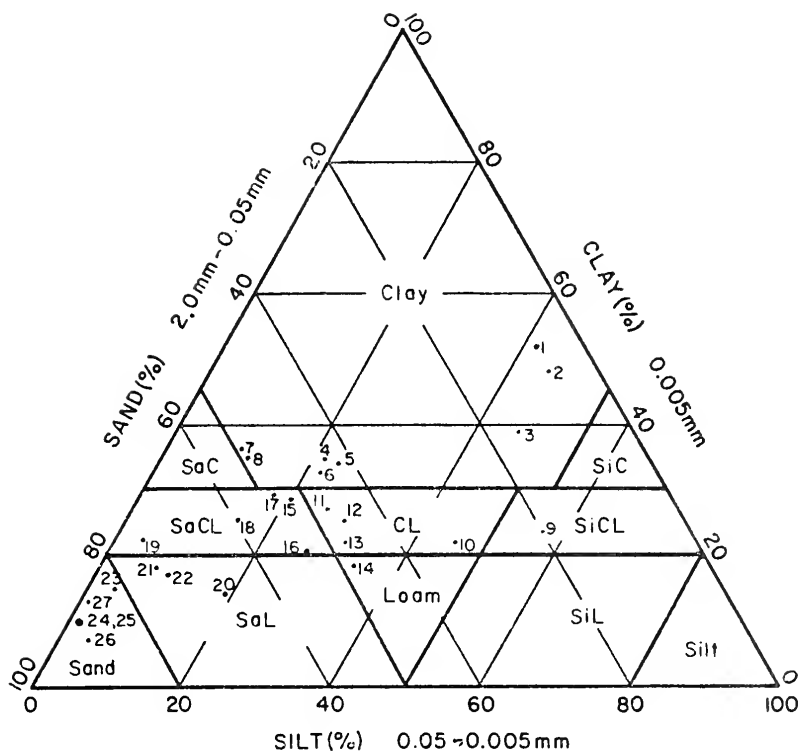
Soil No.	Sand 2.0~0.05 ^{mm} (%)	Silt 0.05~0.005 ^{mm} (%)	Clay ~0.005 ^{mm} (%)	Textural Group
1-75	28	31	41	Clay
1-50	47	21	32	
9-75	36	42	22	Clay Loam
10-75	46	27	27	
1-25	66	11	23	Sandy Clay Loam
(1-15)*	73	7	20	
7-50	68	6	26	
(7-25)*	76	4	20	
(8-75)*	61	9	30	
8-50	68	7	25	
(8-25)*	76	4	20	
10-50	58	20	22	
11-75	56	22	22	
(11-50)*	65	15	20	
15-75	59	16	25	
15-50	67	12	21	
17-75	61	13	26	
17-50	68	9	23	
7-75	61	8	31	Sandy Clay
(8-75)*	61	9	30	
(1-15)*	73	7	20	Sandy Loam
(7-25)*	76	4	20	
(8-25)*	76	4	20	
9-50	52	29	19	
9-25	68	15	17	
10-25	71	12	17	
(11-50)*	65	15	20	
11-25	74	8	18	
15-25	75	7	18	
17-25	76	5	19	

*Parentheses indicate the soils which could be classified in more than one textural group.

Bureau of Public Roads as illustrated in Figures 4 and 5. In Tables 2 and 3, twenty eight soils obtained from different locations of the state of Indiana are listed. These twenty eight soils will hereafter be called "natural" soil samples.

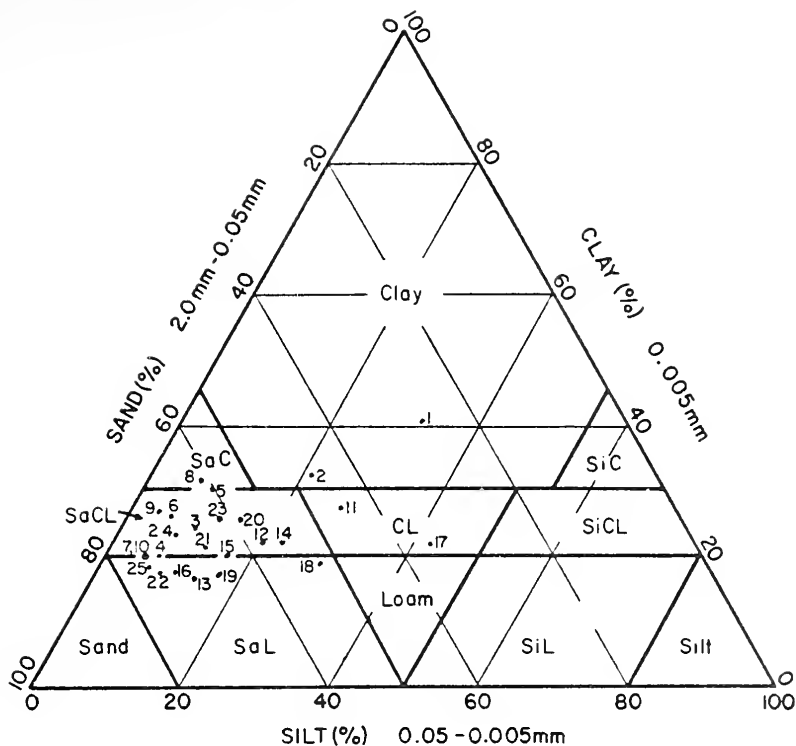
Table 4 shows the soil samples produced by mixing some of the natural soils with varying amounts of sand; these were called artificially prepared soils. Twenty nine soil samples were produced by mixing. In Table 4 the sample numbers shown in parentheses are for the soil samples which could be classified in more than one textural groups.

In numbering these artificially prepared soil samples, the first number preceding the hyphen indicates the natural soil No. which is combined with the sand (No. 27) and the last number indicates the weight percentage of the natural soil (passing #40 sieve) in the final mix. For example, soil No. 1-75 is for the soil which is made up by mixing 75 percent of soil No. 1 with 25 percent of sand (No. 27). In all cases just the material passing the No. 40 mesh sieve was used.



NOTE: NUMBERS NEXT TO DATA POINTS ARE SOIL NUMBERS

FIGURE 4 TEXTURAL CLASSIFICATION OF THE NATURAL SOILS



NOTE: NUMBERS IN THE CHART CORRESPOND TO SOIL NUMBERS AS GIVEN BELOW. (SEE ALSO TABLE 4)

1. 1-75	8. 7-75	14. 11-75	20. 15-75
2. 1-50	9. 7-50	15. 11-50	21. 15-50
3. 1-75	10. 7-25	16. 11-25	22. 15-25
4. 1-15	11. 10-75	17. 9-75	23. 17-75
5. 8-75	12. 10-50	18. 9-50	24. 17-50
6. 8-50	13. 10-25	19. 9-25	25. 17-25
7. 8-25			

FIGURE 5 TEXTURAL CLASSIFICATION OF THE ARTIFICIALLY PREPARED SOILS

PROCEDURES AND TESTS CONDUCTED

Standard Test for Consistency Limits of Soils

The tests to determine both the liquid and the plastic limits of the soil samples were conducted in accordance with ASTM D423-61T (1) and ASTM D-424-59 (2) respectively.

Moisture Tension Test

Preparation

All soil samples to be tested were sieved through the No. 40 sieve and only the portion passing the No. 40 sieve was used for the moisture tension tests.

Each soil sample is put into a glass jar filled with distilled water. To aid in extracting air from the soil particles, the sample and water were first agitated with a spoon. The soil was left standing for 24 hours with approximately 1" height of excess water. About 50 gm of soil was necessary for one run of test.

After a period of 24 hours the excess water on the surface of the soil in the jar was removed taking care not to disturb the soil sample in the jar. The ceramic plates were wetted with distilled water prior to placing the soil on the plate. A sufficient amount of soil was placed in the rubber ring on the plate using a spoon. The ceramic plate was then placed in the extractor, all the tubes connected and the lid of the extractor closed and tightened with bolts.

Application of Pressures

After the soil on the plates is placed in the extractor, air pressure was applied to the soil samples in the extractor. During this process excess water and the water in the soil samples are forced out of the extractor through the outflow tubes which are connected with the ceramic plate cells. The pressure was maintained for 24 hours to reach an equilibrium state. The lid of the extractor was opened after 24 hours and the soil samples were transferred from the plate to a container using a spatula. The moisture content of these soil samples was determined in accordance with ASTM D2216-63T. The water contents of these soil samples was recorded and the pressure specified along with the water content. For example WC_3 designates the water content obtained under a pressure of 3 psi.

Tests for Moisture Tension Curves

To determine the relationship between water content of the soil samples and the pressure applied to the samples, different intensities of pressure were used in the tests. In this study, the pressure intensities were varied between 0.4 psi and 47 psi. Two procedures to apply pressures were used. One is called "a step application of pressure" and the other is "an immediate application of pressure".

In the first procedure, the pressure was started with the lowest intensity of pressure and the pressures were increased step by step to the maximum intensity. In this method, all samples to be tested were prepared on the same day since the number of the samples to be prepared on a certain day is the same as the number of the levels of the pressure to be applied.

To illustrate the above, for example, assume five levels of pressure such as 0.5, 1.0, 2.0, 5.0 and 10.0 psi are to be applied. Using this method, five samples need to be prepared (if no replicates are desired) prior to applying the pressures. All of these samples are placed on the ceramic plate on the same day and the first pressure to be applied must be 0.5 psi. After 24 hours under 0.5 psi, one soil sample is taken out to determine the water content of the soil under 0.5 psi but the other four samples are left in the apparatus. Then the pressure of 1.0 psi is applied, and after 24 hours a sample is taken out and the other three are left. This is continued until all intensities of pressure have been applied and the water content of the soil is determined for each pressure.

The other procedure was to apply the pressure to the sample just once. The sample, thus, was always fresh and had not been subjected to any other pressure prior to the test.

For instance, only one sample may be prepared on the first day if no replicates are desired. Suppose 2.0 psi of pressure is chosen and applied to the first sample. On the next day another sample is prepared for the next pressure, say 0.5 psi, and so on until all pressures are used and the water content is determined for these pressures. Thus, any pressure can be chosen to be applied first by this method.

Tests for Time Factor Study

The purposes of this study were twofold, (1) to find out if a savings in time could be realized by using a higher pressure and (2) make certain that sufficient time was used so that equilibrium was reached.

For this study, four kinds of soils which were expected to require relatively longer equilibrium time were chosen and three different intensities of pressure (1.0, 2.0 and 4.0 psi) were applied. Measurements were done after seven different periods such as 1, 2, 4, 14, 24, 36 and 48 hours. A replicate test was made on each sample.

For each soil and each pressure, fourteen samples were prepared on the same day because seven stages of loading time and a replicate for each were used. These fourteen samples were placed in the extractor and the first pressure was applied (say 1.0 psi). After one hour (first loading period), two samples were taken out to determine the water contents under 1.0 psi for one hour. After 2 hours, two more samples were taken out. This was continued and the last two samples were taken out after 48 hours of pressure application and their water contents were determined.

Tests for Prediction Curves of Atterberg Limits

To obtain prediction curves of the liquid limit, the plastic limit and the plasticity index of soils, by the moisture tension method, two intensities of pressure (3 psi and 20 psi) were selected. An amount of soil sample necessary for two runs of the test was prepared. Half of this amount was used for the 3 psi pressure and the other half for the 20 psi pressure. The tests were run according to the procedure described earlier.

RESULTS

Consistency Limits by the Standard Method

Both the liquid and plastic limits were determined for the twenty seven natural soils (see Table 5) and thirty artificially prepared soils. Several operators ran the tests on different days for the natural soils, but for the artificially prepared soils, both the liquid limit and plastic limit values were determined by only one operator.

The liquid and plastic limits for the natural soils are shown in Table A-1 and Table A-2; their standard deviations and average values are shown in Table 6 and Table 7. The test results for the artificially prepared soils are shown in Table A-3 along with the results of the moisture tension tests using 3 psi and 20 psi of pressure.

The standard liquid limits of the natural soils ranged between 19.3% and 58.1%. The standard deviation for each operator was approximately 1.5%, the highest was 4.66% for soil No. 28 by operator C as shown in Table 6. The deviation between operators from the average value for each soil was between 5% and 10%.

As for the plastic limits, the natural soils had values of between 14.0% and 29.0%. The standard deviation for each operator was between 0.46% and 5.42% which was somewhat higher than it was for the liquid limits. Also the maximum deviation between operators was 15%.

Table 8 and Table 9 show the cases set up for LL (Liquid Limit) and PL (Plastic Limit) respectively. These tables also show the results of this analysis in the right column.

Table 5. Number of Tests Conducted on Natural Soils

Method	LL & PL by ASTM Standard Method										WC ₃ & WC ₂₀ by Moisture Tension			
Operator	A		B		C		D		E		F	G	H	I
Soil No.	LL	PL	LL	PL	LL	PL	LL	PL	LL	PL	LL	PL		
1					5	5	5	5	1	1	1	1	3	3
2	1	1	1	1							1	1	5	
4	5	5	5	4					1	1	1	1	5	3
5	2	2	2	2							1	1	5	3
6	5	5	5	5	5	5	5	5			1	1	3	
7			1	1							1	1	5	3
8					5	5	5	5	1	1	1	1	5	3
9	1	0							1	1	1	1	5	3
10	1	1									1	1	5	3
11	5	5	5	5					1	1	1	1	5	3
12	1	1	1	1					1	1	1	1	5	3
13	5	5	5	5							1	1	1	-
14	1	1									1	1	5	3
15	1	1	1	1							1	1	5	3
17	5	5	1	1	5	5	5	5	1	1	1	1	5	3
18	5	3	1	1					1	1	1	1	5	3
19	1	1	1	1					1	1	1	1	5	3
22	1	1	1	1							1	1	5	3
28					5	5	5	5					5	3

Table 6. Liquid Limit Values by Several Operators

Operator Soil	A (%)	B (%)	C (%)	D (%)	E (%)	F (%)	Grand Average (%)
1			49.4 (4.07)	50.4 (1.69)	51.0	48.0	50.0
2		38.5				47.8	43.2
4	27.9 (1.01)	28.0 (0.77)			31.1	34.8	28.8
5	25.1 (0.57)	25.2 (1.20)				24.5	25.0
6	27.4 (1.24)	27.1 (1.06)	29.6 (1.51)	27.6 (0.97)		32.2	28.1
7		26.3				27.7	27.0
8			27.9 (0.30)	30.0 (1.11)	27.5	26.5	28.7
9	30.4					30.5	30.5
10	21.5					18.7	20.1
11	20.3 (0.51)	19.8 (0.48)			20.8	20.8	20.2
12	23.5	22.2			21.4	22.6	22.4
13	42.2 (1.34)	41.4 (1.59)				39.2	41.6
14	18.4					17.7	18.1
15	25.8	20.3				19.5	21.9
16						N.P.	
17	19.1 (0.35)	19.0	19.7 (0.78)	19.5 (0.38)	18.4	18.6	19.3
18	23.4 (1.25)	22.9			20.5	23.0	23.0
19	30.8	27.6			29.4	24.8	28.2
20	N.P.					N.P.	

Table 6, cont.

Operator Soil	A (%)	B (%)	C (%)	D (%)	E (%)	F (%)	Grand Average (%)
21	N.P.					N.P.	
22	24.9	22.7				20.9	22.8
23	N.P.					N.P.	
24	N.P.					N.P.	
25	N.P.					N.P.	
26	N.P.					N.P.	
27	N.P.					N.P.	
28			58.7 (4.66)	57.5 (0.78)			58.1

(Numbers in parentheses are standard deviation.)

Table 7. Plastic Limit Values by Several Operators

Operator Soil	A (%)	B (%)	C (%)	D (%)	E (%)	F (%)	Grand Average (%)
1			29.7 (2.06)	28.8 (1.76)	29.2	25.8	28.9
2	28.8	16.8*				26.3	27.6
4	15.6 (2.13)	12.5*			14.4	17.9	15.7
5	15.7 (1.13)	13.6*				16.6	16.0
6	15.9 (2.88)	14.4*	21.0 (1.09)	18.4 (0.65)		16.3	18.3
7		11.9*				16.4	16.4
8	13.2		16.8 (0.53)	15.8 (0.88)	14.0	16.4	15.9
9					23.5	25.3	24.4
10	N.P.					N.P.	
11	13.7 (1.38)	11.7*			14.8	15.5	14.1
12	14.8	13.5*			17.7	20.4	17.6
13	33.7 (2.55)	29.2*			31.5		33.4
14	N.P.					N.P.	
15	16.7	10.1*				13.9	15.3
16						N.P.	
17	13.1 (1.00)	11.0*	14.9 (0.65)	14.0 (0.46)	13.9	13.4	14.0
18	16.5 (2.25)	11.4*			14.7	15.2	15.9
19	21.2	14.0*			18.2		19.7
20	N.P.					N.P.	

Table 7, cont.

Operator Soil	A (%)	B (%)	C (%)	D (%)	E (%)	F (%)	Grand Average (%)
21	N.P.					N.P.	
22	18.0	13.8*				17.0	17.5
23	N.P.					N.P.	
24	N.P.					N.P.	
25	N.P.					N.P.	
26	N.P.					N.P.	
27	N.P.					N.P.	
28			29.3 (5.42)	28.8 (1.04)			29.0

*Operator B's data is not included in calculation of the average.

Table 8. Tests for Operator Effect (LL)

Case	Test Method	Operators	Soil No.	No. of Replicas	Result
1	Two-way ANOVA	A,B,C,D	6,17	1 & 5	Not Reject
2	Two-way ANOVA	A,B	4,5,6,11, 13,18	1 or 2 or 5	Not Reject
3	Two-way ANOVA	C,D	1,6,8,17, 28	5	Not Reject
4	t-test	A,B	12,15,19,22	1	Not Reject
5	t-test	A,F	2,9,10,12, 14,15,22	1	Not Reject
6	t-test	B,F	2,7,12,15, 17,18,19,22	1	Not Reject
7	t-test	E,F	1,4,8,11, 12,17,18,19	1	Not Reject

Table 9. Tests for Operator Effect (PL)

Case	Test Method	Operators	Soil No.	No. of Replicas	Result
1	Two-way ANOVA	A,B,C,D	6,17	1 & 5	Not Reject
2	Two-way ANOVA	A,B	4,5,6,11, 13,18	1 or 2 or 5	Reject
3	Two-way ANOVA	C,D	1,6,8,17, 28	5	Not Reject
4	Two-way ANOVA	A,C,D	6,17	5	Not Reject
5	t-test	A,B	12,15,19,22	1	Reject
6	t-test	A,F	2,12,15,22	1	Not Reject
7	t-test	B,F	2,7,12,15, 17,18,22	1	Not Reject
8	t-test	E,F	1,4,8,11, 12,17,18	1	Not Reject

In the case of soils for which more than two operators obtained at least one observation, such as case 1 through case 3 (Table 8) in liquid limit, a two-way ANOVA was utilized. For the calculation the computer program UNEQUAL was utilized. All factors were assumed random models. This technique was also used in cases 1 through 4 of the plastic limit. For the soils which have only one observation by one operator, as case 4 through case 7 for the liquid limit and case 5 through case 8 for the plastic limit, t-tests were utilized. The analysis and the calculations for all cases are shown in Table B-1 through Table B-4. The assumptions made are also shown.

The results of the tests of operator effect are shown in the right column in Table 8 for liquid limit and Table 9 for plastic limit. As for the liquid limits, the null hypothesis that "technique of each operator has no effect" was accepted. In other words, there was no significant difference between the operators tested in each case. For the plastic limits, case 2 and case 5 were rejected. By examining the original data for both cases, it was seen that the plastic limits obtained by operator B were always smaller than the others and he measured a plastic limit as low as 11%. It is doubtful that a plastic limit of 11% obtained by the standard method is reliable. It seems reasonable to assume that operator B had poor or wrong techniques in obtaining plastic limits. Case 4 in Table 9 shows that the hypothesis that operator technique had no effect can be accepted when operator B's data is omitted; therefore, operator B's data will be omitted in the following analysis.

The analysis for the cases studied show that there is no significant difference due to operators in both liquid and plastic limits.

It does not mean, however, that the observed values of the liquid and plastic limits by the standard tests were accurate or had small operator variance. This may be because of the large variances in the replicate tests that were performed by the operators. It was expected that the variance within operators would be a function of soil type which might be similar for all operators. However, such a tendency could not be observed due to limited data.

Prediction of the Plasticity of Soils by the Moisture Tension Method

In order to find prediction curves of both liquid and plastic limits of soils, the water content at equilibrium under 3 psi and 20 psi pressure in the pressure plate apparatus was determined. The tests were run for both the natural soils and the artificially prepared soils.

The data for the natural soils were obtained by three operators. One of the operators ran the tests under the same condition on five different days and the other two operators ran them on three different days. For the artificially prepared soils, one operator used both the standard method and the moisture tension method. The tests were not replicated.

All observed WC_3 and WC_{20} by three operators are shown in Tables A-4 through A-9. Also the standard deviations among operators for each soil are shown in the same tables. The results for the artificially prepared soils is shown in Table A-3 and Figure A-1 through Figure A-3 along with the standard test results.

For the moisture tension test results, a two-way ANOVA was utilized to test operator effect on the mean value. In the analysis, both factors of operator and soil type were assumed random models.

Table 10. Two-way ANOVA of WC₃ and WC₂₀ by Three Operators

Case	Source	S.S.	D.F.	M.S.	F	Critical F
WC ₃	Operator	10.88	2	5.44	0.66	19.5*
	Soil	10,308.88	14	736.35	1/F = 1.52	
	Ope · Soil	231.22	28	8.26		
	Error	269.21	120	2.24		
WC ₂₀	Operator	17.74	2	8.87	4.78	5.45**
	Soil	5,829.05	14	416.36		
	Ope · Soil	51.94	28	1.86		
	Error	80.96	120	0.67		

* $\alpha = 0.05$ ** $\alpha = 0.01$
 Model: $Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \epsilon_{(ij)k}$

The results are shown in Table 10. According to this analysis, there is no significant difference between operators at the 99% level of significance.

In order to find prediction curves of the consistency limits of soils using the moisture tension results, a regression analysis was made using the liquid or the plastic limits as the dependent variables and WC_3 and WC_{20} as the independent variables.

Due to the fact that the same number of tests were not made on all soils, two processes of analysis were adopted. One is called "all random combinations" and the other is called "random pull". For the artificially prepared soils, a regression analysis was made using only one observation of the liquid limit and the plastic limit for each soil and WC_3 and WC_{20} .

For making regression analysis, BMD2R and BMD3R of computer program were utilized.

All Random Combinations

Because of the number of observations of both liquid and plastic limits as the dependent variables were not the same as those of WC_3 and WC_{20} , not all the values obtained could be used in the regression analysis. The values used in the regression analysis were obtained from the set of all available observations for each test method combined randomly. For example, the number of the liquid limits observed for soil No. 1 was twelve and that of WC_3 and WC_{20} in the moisture tension method was eleven. In this case the data of soil No. 1 for the analysis was obtained so that the eleven observations of WC_3 and WC_{20} were randomly combined with the eleven of the liquid limits observations out of twelve.

An assumption made for this process, that there is no significant difference due to operator variability in both test methods, has been already discussed in the above section of this chapter. The data which were chosen from both the standard test results and the moisture tension results and combined randomly are shown in Table C-1.

Prior to starting the regression analysis, the assumption of homogeneity of variance was examined. The results are shown in Table 11.

Table 11. Homogeneity of Variance Calculated for the Data Shown in Table C-1 by the Foster-Burr Test

	Calculated q	Critical Q	Result
L.L.	0.1179	0.100**	rejected
P.L.	0.1001	0.113*	not rejected

* $\alpha = 0.05$

** $\alpha = 0.01$

With the plastic limits as a dependent variable, the test showed no significant difference in the variance at the 95% level of significance. The homogeneity of variance test for the liquid limits, however, was violated at the 99% level of significance. Some attempts to decrease the variances of the liquid limits were made. One of them was to use a square root of the liquid limit value as a dependent variable. Another attempt was to group the soils using the relationship between WC_3 and WC_{20} . However, all were not successful. The results of the above regression analysis are shown in Table 12.

Random Pull

Another method used to correlate the consistency limits of soils with the moisture tension results was called random pull which was made

to eliminate some shortcomings in the all random combination process. This process is one in which only one pair of WC_3 and WC_{20} values for each soil type were chosen randomly as the independent variables from the original data, but for the dependent variables, the mean value of all observed liquid and plastic limits were used for each soil type. Thus, only one set of LL and PL and WC_3 and WC_{20} for each soil type was used; therefore, in the case of the liquid limit, 18 cases were available for the regression analysis, this number being the same as that of the soil type. The combination chosen for the regression analysis is shown in Table C-2. The results of the regression analysis are also summarized in Table 12.

Analysis of the Artificially Prepared Soils

For the artificially prepared soils, the standard tests and the moisture tension tests were run once by one operator. Therefore, only one set of LL (or PL), WC_3 and WC_{20} for each soil type were available for regression analysis. In the above procedure the liquid limit or the plastic limit was used as the dependent variable and both WC_3 and WC_{20} were used as the independent variables. The results of the regression analysis are shown in Table 13.

Interpretation of the Regression Analysis Results

There were a number of problems that made analysis difficult. First, sufficient numbers of data by the standard method corresponding to the number of data by the moisture tension method could not be obtained because of the length of time required to run the standard tests for a large number of samples. In some cases, no data were obtained by the same operator in both tests.

Table 12. Prediction Equations for Consistency Limits

(natural soils)

Dependent Variable	Analysis Method	Independent Variable	Model	R ²	Std. Error	No. of Samples	F
L.L.	All Combination	$(WC_{20})^2$	$\hat{Y} = 14.97 + 0.0416 X_1$	0.91	3.87	104	1027.4
		$(WC_3)^2$	$\hat{Y} = 11.72 + 0.0207 X_2$	0.85	4.94	104	586.9
		$(WC_3)(WC_{20})$	$\hat{Y} = 13.10 + 0.0301 X_3$	0.91	3.90	104	1009.9
	Random Pull	$(WC_{20})^2$	$\hat{Y} = 15.95 + 0.0399 X_1$	0.88	3.99	18	112.5
		$(WC_3)^2$	$\hat{Y} = 12.46 + 0.0186 X_2$	0.79	5.15	18	61.2
		$(WC_3)(WC_{20})$	$\hat{Y} = 16.03 + 0.0283 X_3$	0.87	4.00	18	111.8
P.L.	All Combination	$(WC_{20})^2$	$\hat{Y} = 12.09 + 0.0179 X_1$	0.83	2.62	81	380.5
		$(WC_3)^2$	$\hat{Y} = 10.38 + 0.0093 X_2$	0.86	2.39	81	471.2
		$(WC_3)(WC_{20})$	$\hat{Y} = 11.17 + 0.0132 X_3$	0.86	2.39	81	471.7
	Random Pull	$(WC_{20})^2$	$\hat{Y} = 13.35 + 0.0168 X_1$	0.71	2.93	16	34.2
		$(WC_3)^2$	$\hat{Y} = 11.58 + 0.0086 X_2$	0.81	2.37	16	60.0
		$(WC_3)(WC_{20})$	$\hat{Y} = 12.43 + 0.0122 X_3$	0.77	2.62	16	46.2

All values significant at $\alpha = 0.05$ level

Table 13. Prediction Equations for Consistency Limits

(artificially prepared soils)

Dependent Variables	Independent Variables	Models	R ²	Std. Error	No. of Samples	F
L.L.	$(WC_{20})^2$	$\hat{Y} = 14.99 + 0.0504 X_1$	0.88	2.44	29	190.6
	$(WC_3)^2$	$\hat{Y} = 13.58 + 0.0178 X_2$	0.87	2.52	29	178.0
	$(WC_3)(WC_{20})$	$\hat{Y} = 13.76 + 0.0323 X_3$	0.94	1.77	29	389.0
P.L.	$(WC_{20})^2$	$\hat{Y} = 12.78 + 0.0208 X_1$	0.62	2.27	19	27.6
	$(WC_3)^2$	$\hat{Y} = 10.97 + 0.0093 X_2$	0.92	1.06	19	187.1
	$(WC_3)(WC_{20})$	$\hat{Y} = 11.61 + 0.0150 X_3$	0.80	1.65	19	67.8
P.I.	$(WC_{20})^2$	$\hat{Y} = 2.73 + 0.0279 X_1$	0.83	1.77	19	81.6
	$(WC_3)^2$	$\hat{Y} = 2.42 + 0.0091 X_2$	0.66	2.48	19	33.2
	$(WC_3)(WC_{20})$	$\hat{Y} = 2.06 + 0.0176 X_3$	0.82	1.82	19	75.6

All values significant at $\alpha = 0.05$ level

Table 14. Prediction Equations for Consistency Limits
(Utah Soils from Sultan)

Dependent Variables	Independent Variables	Models	R ²	Std. Error	No. of Samples	F
L.L.	$(WC_{20})^2$	$\hat{Y} = 18.59 + 0.0154 X_1$	0.76	3.57	55	164.8
	$(WC_3)^2$	$\hat{Y} = 15.20 + 0.0138 X_2$	0.78	3.39	55	189.7
	$(WC_3)(WC_{20})$	$\hat{Y} = 17.27 + 0.0145 X_3$	0.78	3.37	55	192.5
P.L.	$(WC_{20})^2$	$\hat{Y} = 18.78 + 0.0040 X_1$	0.35	2.38	31	15.8
	$(WC_3)^2$	$\hat{Y} = 17.33 + 0.0041 X_2$	0.46	2.17	31	24.9
	$(WC_3)(WC_{20})$	$\hat{Y} = 18.25 + 0.0040 X_3$	0.40	2.30	31	19.2

Significant at $\alpha = 0.05$ level

Secondly, the variances of the standard method test results among and within operators were not consistent. For some soils the results of a single operator had large variances that were not evident with other operators. In other words, no relationship could be found between soil type and operator regarding magnitude of the variance. Dawson (6) has reported, however, that the overall variation of the liquid limits values due to operator technique was as high as $\pm 5\%$ to $\pm 10\%$ even by experts of the standard test method.

In the "all random combination" process, the homogeneity of variance of the dependent variables (LL) was violated. This non-homogeneity was no doubt, due to large operator variances.

In the "random pull" process the analysis was made for only one pair of observations for each soil. In this case, no consideration was given to the variance of the observed values in both test methods and the mean value of some observations was assumed to be the "true" value for each soil. The assumption for this process, that there is no significant difference due to operators has been already established in both test methods. In the analysis of the artificially prepared soils, only one observation could be used for each soil.

It is significant that the variables chosen in the regression analysis as the variables which have high correlation with both the liquid and plastic limits were $(WC_{20})^2$, $(WC_3)^2$ and $(WC_3)(WC_{20})$ as shown in Table 12 and Table 13. In the artificially prepared soils, for which only one observation per soil was obtained by one operator, similar results were obtained. For the plasticity index (PI), the difference of LL and PL, these variables shown above also have a relatively high correlation with PI. In Table 13, a calculated model for

PI of the artificially prepared soils is shown. Moreover, the variables of $(WC_{20})^2$, $(WC_3)^2$ and $(WC_3)(WC_{20})$ in Sultan's data (14) show high correlation with the liquid limits as shown in Table 14. In case of the plastic limit in Sultan's data, a relatively low standard error of estimate is shown though R^2 is as low as 0.46.

At this stage of the study, however, it is not possible to determine which model is the best. However, it is believed that reasonable values can be found to represent both the liquid and plastic limits by using one of the models.

The question of the reliability of the moisture tension tests was considered. For the originally observed values of WC_3 and WC_{20} , as discussed in the preceding sections of this section, there was no significant difference due to operators. Another test for its reliability was made by using the coefficient of variation which is denoted as the standard deviation divided by the mean value. Table D-1 through Table D-3 show these values calculated for the predicted liquid limits and plastic limits by using the equations determined in the above analysis. Comparing the coefficients of variation of the standard test results with those of the predicted values by the moisture tension method for each soil, it is seen that the latter has smaller values of the coefficient for many soil types. This tendency is quite apparent especially in the plastic limit. As a result, it can be concluded that the predicted values by the models have more, or at least as much, reliability as the standard test results.

Prediction of Non-Plasticity by WC_3 and WC_{20}

In Figure 6, the observed values of WC_3 and WC_{20} for the natural and the artificially prepared soils are plotted. Arbitrarily selected boundaries have been drawn delineating the non-plastic materials from the plastic materials. Data on this figure suggest a technique for distinguishing between plastic and non-plastic materials.

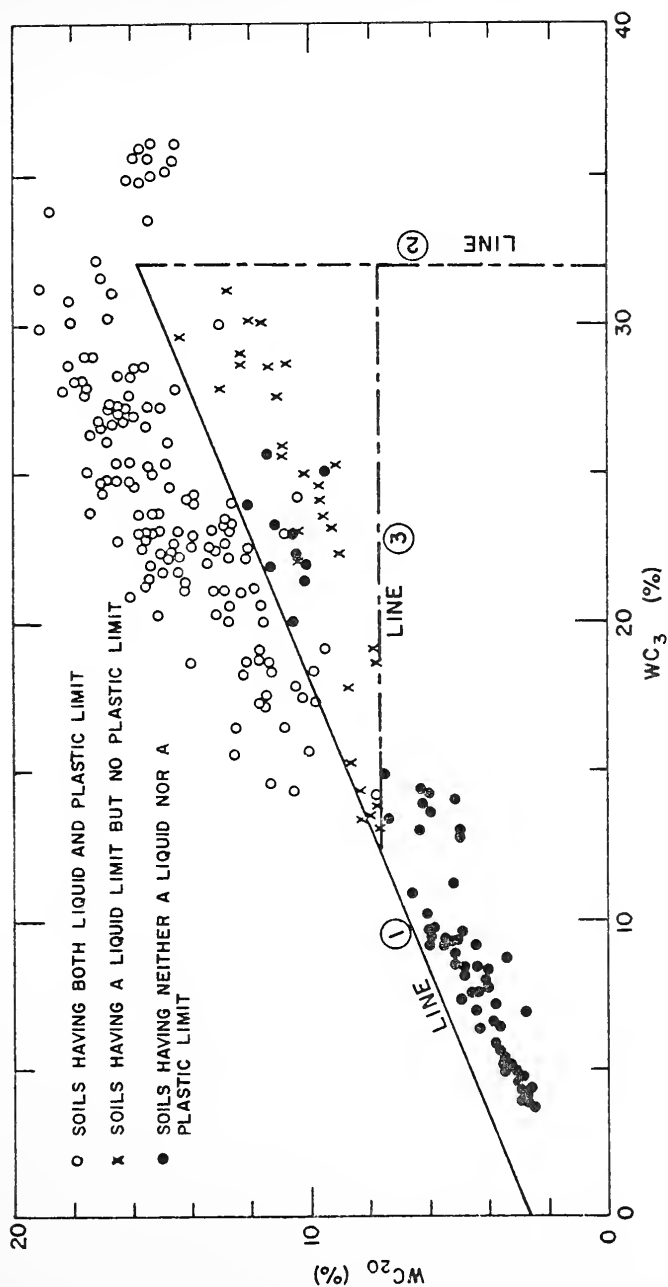
Some Characteristics of the Moisture Tension Method

In this section, some characteristics observed in the moisture tension test results will be discussed qualitatively. It had been anticipated that these characteristics could be used in the prediction equations of the consistency limits of soils and, therefore, increase the reliability of prediction. The attempts to do this did not appear to improve the results. However, they will be discussed here since they should give the reader greater insight into the mechanical functioning of the moisture tension method and facilitate the undertaking of studies in this area.

Shape of Moisture Tension Curves

The moisture tension curves for various soils are shown in Figures E-1 through E-10.

Many soils show two flex points on their moisture tension curves, some of them have only one flex point and others show almost a straight line relationship between log pressure and water content. As only a few curves were obtained for most soil types, full consideration could not be given to the shapes of these curves. It can be seen, for example, that for the clays, not all the curves are similar. The primary thing that can be observed in the study for the soils which have two flex



NOTE: LINES ARBITRARILY DRAWN TO INCLUDE MOST SAMPLES IN EACH CATEGORY

FIGURE 6 SUGGESTED BOUNDARY LINES — NON PLASTIC SOILS

points is that the lower flex point occurs at about 1.5 to 3 psi of pressure and the upper flex point occurs at around 10 to 30 psi of pressure. However, the soils which have only one flex point, such as soil No. 7 may have another flex point above the range of pressure applied.

Some attempts were made to find relationship between soil composition and the shape of the moisture tension curve. The results of this study will be discussed in the next section.

The Relationship Between Soil Composition and Moisture Tension

The soil composition shown in Tables 3 and 4 are not totally suitable to specify the properties of the soils, since the classification depends upon the amount of the soil finer than 2mm, whereas the soil samples used for all tests passed the No. 40 sieve. Table F-1 shows the soil compositions based on the sizes No. 40 mesh sieve, 0.05mm and 0.005mm. In the following sections, this classification will be used. For convenience, the fraction passing the No. 40 sieve and retained in the 0.05mm will be called "coarse portion", the fraction between 0.05mm and 0.005mm as "medium portion" and the fraction smaller than 0.005mm as "fine portion". They are expressed as percent by weight.

Figure F-1 through Figure F-8 show the relationships between the soil composition and water content by the moisture tension method. From these figures the following may be observed.

1. Coarse portion

low WC_3	fair correlated (Figure F-1)
low WC_{20}	relatively scattered (Figure F-5)
low $(WC_3 - WC_{20})$	relatively scattered (Figure F-7)

2. Medium portion

high WC_3	very scattered (Figure F-2)
high WC_{20}	very scattered (Figure F-6)
high $(WC_3 - WC_{20})$	very scattered (Figure F-8)

3. Fine portion

high WC_3	relatively scattered (Figure F-2)
high WC_{20}	better correlated (Figure F-4)
high $(WC_3 - WC_{20})$	

From the above, it can be concluded that sands show low WC_3 , WC_{20} and $(WC_3 - WC_{20})$; clays show high WC_3 , WC_{20} and $(WC_3 - WC_{20})$. The soils whose medium portion is predominant may have a large difference of WC_3 and WC_{20} . Silts may belong to this type of soil. (See soil No. 9 in Figure 7.) A small difference in the fine portion causes a larger difference in WC_3 and WC_{20} than in the other two portions. This means that the fine portion will have a predominant effect mostly on both WC_3 and WC_{20} (Figure F-8).

The difference between WC_3 and WC_{20} is related to the slope of the moisture tension curves. In Figure 9, it is also shown as a distance between WC_{20} and a point on the 45 degree line. Silts, in which the medium portion is predominant, plot far below the 45 degree line in a WC_3 vs. WC_{20} plot (See Figure 7 and Figure 8). Sands plot in the lower left and clays in the upper right.

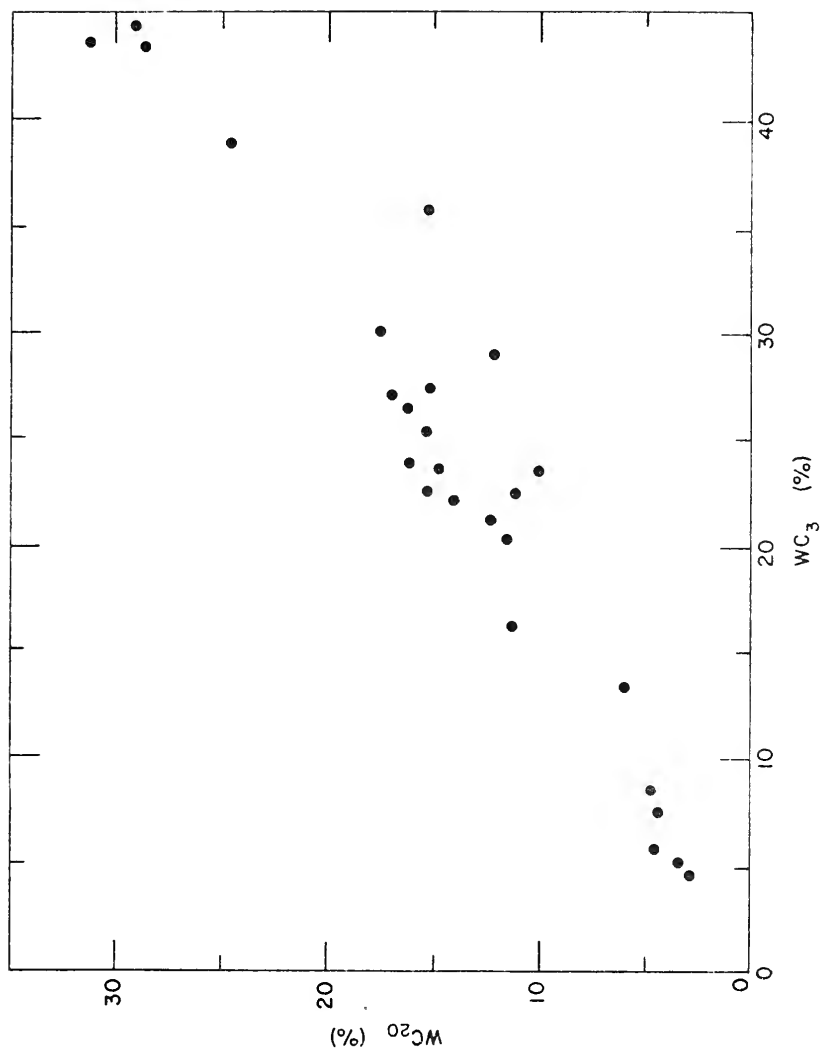


FIGURE 7 RELATIONSHIP BETWEEN WC_3 AND WC_{20} (NATURAL SOILS)

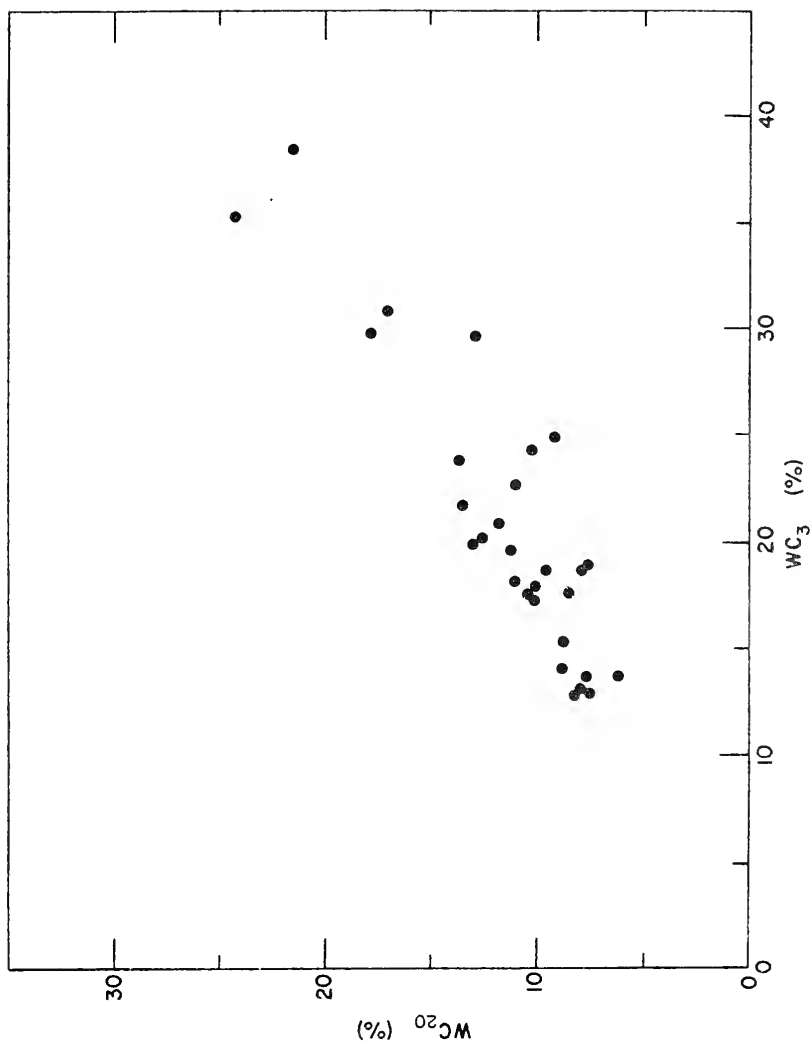


FIGURE 8 RELATIONSHIP BETWEEN WC_3 AND WC_{20} (ARTIFICIALLY PREPARED SOILS)

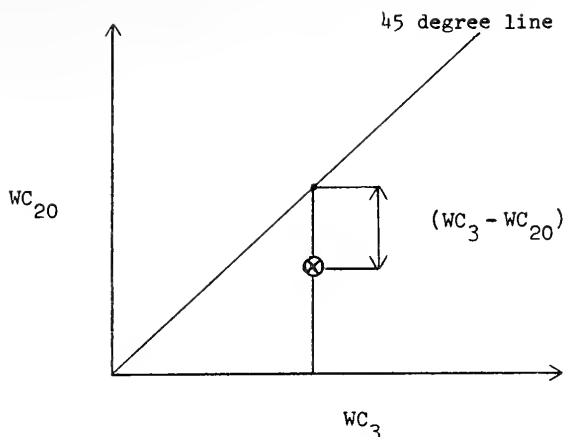


FIGURE 9. RELATIONSHIP BETWEEN WC_3 AND WC_{20}

These relationships may be useful in determining soil composition and classifying them; thus, it can be seen that the slope of a moisture tension curve may have great importance.

An attempt was made to express the slope in meaningful terms. It appears reasonable to assume that the relationship between log pressure and water content is linear between the range of 3 psi and 20 psi of pressure. Then

$$\log p = a + b w \quad (1)$$

where

p = pressure (psi)

w = water content at equilibrium under the pressure p (%)

WC_3 is moisture content at 3 psi of pressure and WC_{20} moisture content at 20 psi; then

$$\log 3 = a + b WC_3, \text{ and}$$

$$\log 20 = a + b WC_{20}$$

From these equations, the following equations are valid.

$$WC_{20} = \frac{\log 20 - a}{\log 3 - a} WC_3 \quad (2)$$

or

$$WC_{20} = WC_3 - \frac{1}{b} \log \left(\frac{3}{20} \right) \quad (3)$$

From equation (2), it can be shown that, if a property of a soil can be expressed only by the intercept (coefficient a) of the moisture tension curve, then WC_{20} can be predicted from WC_3 thus simplifying the procedure. The need for further research on the slope of the curve is indicated.

Factors Affecting the Moisture Tension Method

Equipment and Ceramic Plate

One of the factors affecting moisture tension results is the magnitude of applied pressure. In this study data were not collected to examine the influence of small variations in pressure on the results; however, it can be seen from the moisture tension curves that water content is influenced more by pressure variations at low pressure than at high pressures. Further, this effect is different for different soils. In case of soil 13 in Figure E-5, equilibrium water content at 1.0 psi pressure was 52.5% and at about 1.2 psi equilibrium was 50.0% moisture. Hence, increase in pressure at around 1.0 psi resulted in a 5% decrease of water content. Variation in the applied pressure was observed and recorded during tests. In the case of 3 psi applied pressure, the maximum difference from the 3 psi applied pressure was 0.2 psi. However, there was generally not this much change in pressure during the tests since careful adjustment of valves and regulators and periodic checks on the system insured consistency of the desired pressure.

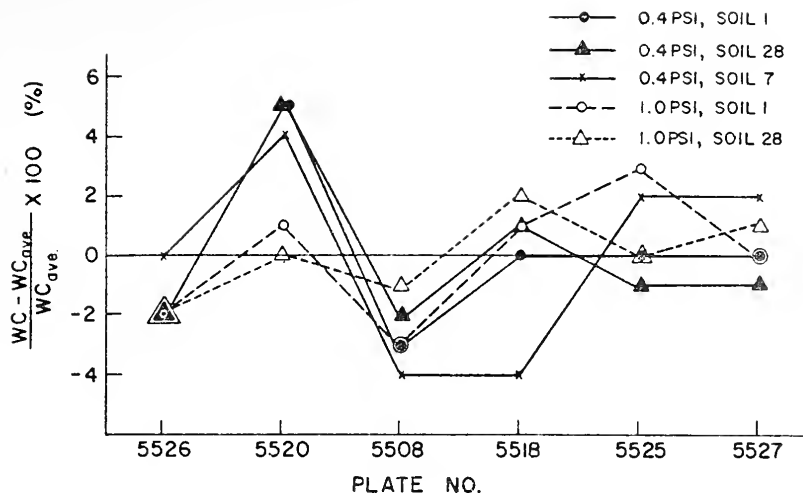


FIGURE 10 WATER CONTENT VARIATION BETWEEN PLATES

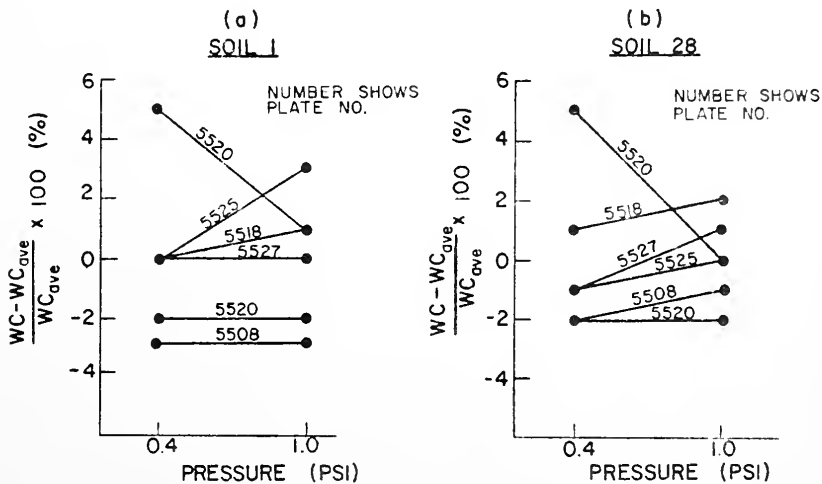


FIGURE 11 THE CHANGES OF WATER CONTENT DEVIATION BY PRESSURES

The influence of using different ceramic plates was evaluated by replicating the same soils under the same pressure using different plates. The results are shown in Table A-10 and Figures 10 and 11. A difference between plates were observed. However, the deviation from the mean value was less than $\pm 5\%$ for a given water content. In this study the influence of different plates on the results was assumed to be negligible.

Time Factor Study

The materials used for this study were soil No. 2, No. 3, No. 5 and No. 6. Each of these soils are clays. A total of seven loading periods were used; 1, 2, 4, 13 (or 14 or 16), 24, 36 and 48 hours. The intensities of the pressure applied were 1.0, 2.0 and 4.0 psi.

The test method has been described in previous paragraphs. The results are shown in Table A-11 and Figure 12 through Figure 15.

In all the figures the abscissa denotes the loading time in log hours; the loading time is the elapsed time during which the pressure is maintained. The ordinates of the graphs represent the moisture content of the soil samples. All these figures show, as expected, that moisture content of a soil by this method is a function of loading time and that it decreases as the length of time is increased. Though the plots are scattered in some cases, it can be said that equilibrium is attained within about 6 to 8 hours after the pressure is applied. However, it may not be said that the elapsed time to reach equilibrium by a higher pressure is always shorter than that by a lower pressure. The results of this study have indicated that a period of 24 hours as used in all the tests in this study is sufficient for attaining equilibrium.

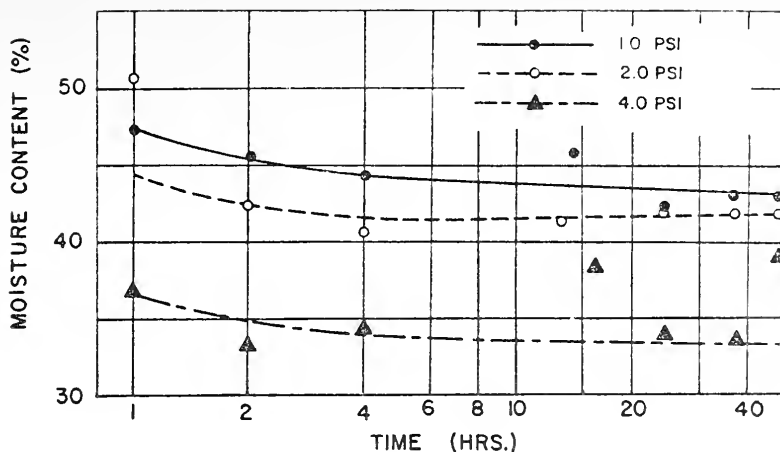


FIGURE 12 EFFECT OF TIME AND PRESSURE ON MOISTURE CONTENT
SOIL NO. 2

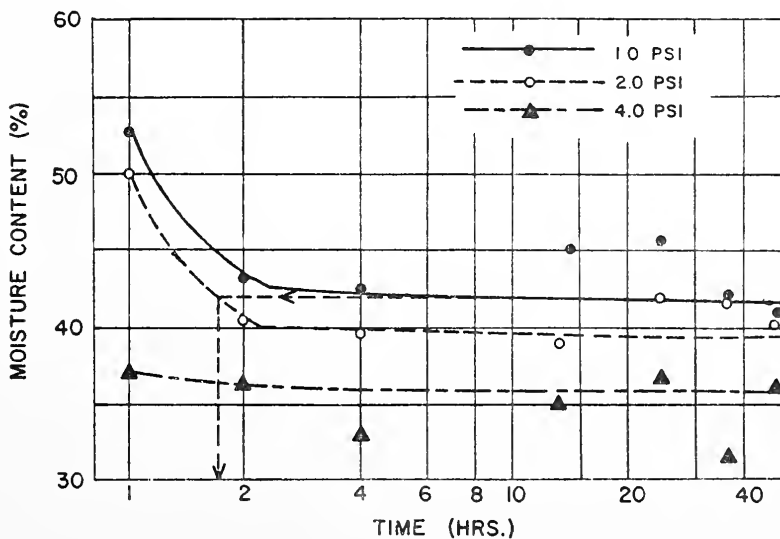


FIGURE 13 EFFECT OF TIME AND PRESSURE ON MOISTURE CONTENT
SOIL NO. 3

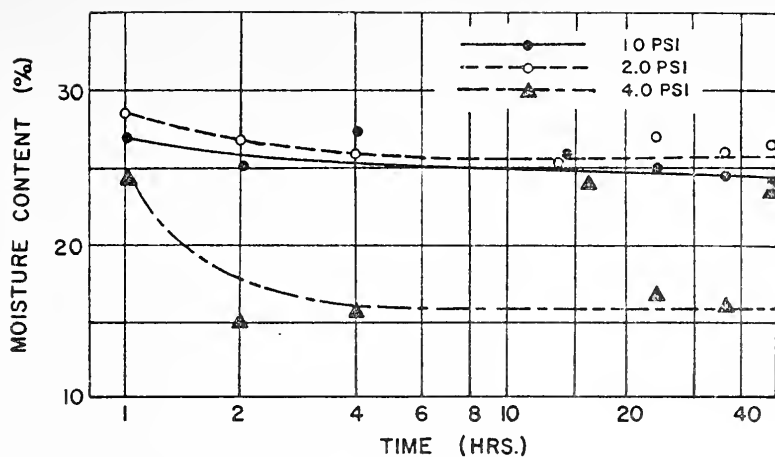


FIGURE 14 EFFECT OF TIME AND PRESSURE ON MOISTURE CONTENT
SOIL NO. 5

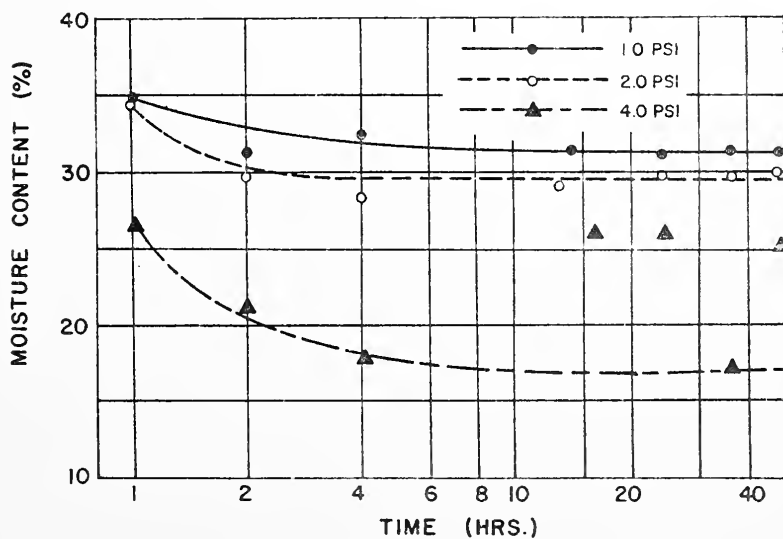


FIGURE 15 EFFECT OF TIME AND PRESSURE ON MOISTURE CONTENT
SOIL NO. 6

In this study the relationships between intensity of pressure, the time for equilibrium and moisture content were investigated further in an effort to make the method faster and thus more economical.

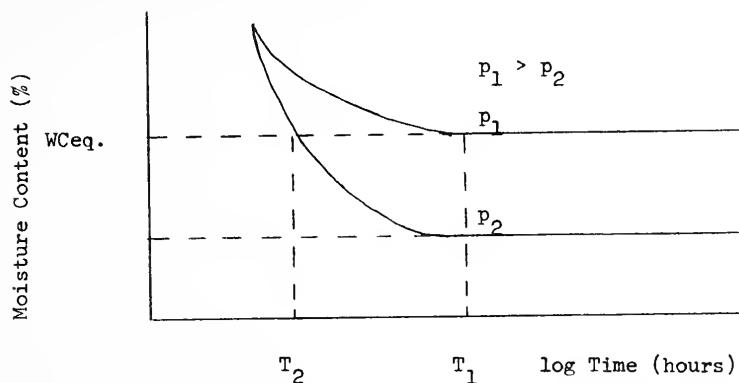


FIGURE 16. EFFECT OF PRESSURE AND LOADING TIME ON EQUILIBRIUM MOISTURE CONTENT.

Figure 16 illustrates the effect of pressure. Assume that T_1 denotes the time necessary to reach the equilibrium water content WC_{eq} under a low pressure p_1 ; a higher pressure p_2 would yield the same water content of WC_{eq} in a shorter time T_2 . If the test results are examined for this purpose, then in Figure 13 the dotted line shows a similar relation as in Figure 16. This means that if the moisture tension test was performed to obtain the equilibrium water content under a pressure of 1.0 psi, it would take at least 8 hours. However, using a pressure of 2.0 psi the necessary time for obtaining the same water content would be two hours. If other figures are examined, it can be noted that this was not always true. In other words, T_2 did not bear the same relation to T_1 for all the soils.

SUMMARY AND RECOMMENDATIONS

The conclusions and recommendations for further study given below are based upon an investigation of one type of soil moisture tension device. In all probability, each type of instrument has its own characteristics and to make the method generally applicable, it would be necessary to calibrate each specific device. The primary purpose of this study was to investigate the factors affecting the method of test and to evaluate the feasibility of using the moisture tension technique for predicting the Atterberg limits of several Indiana soils.

Additional work needs to be done to clarify some of the factors which were studied. Nevertheless, the results of this study have pointed out many interesting conclusions and have suggested the feasibility of the method. All conclusions listed below apply specifically to the devices used in this study and to the methods of test imposed in the laboratory.

1. The values of $(WC_{20})^2$, $(WC_3)^2$ and $(WC_3)(WC_{20})$, which were obtained from the moisture tension method, using 3 psi and 20 psi of pressure, showed high correlations with the liquid and plastic limits and the plasticity index as shown in Table 12 and Table 13. These correlations were found to be independent of soil textural classification.
2. The relationship between WC_3 and WC_{20} in the moisture tension method was found to be dependent upon soil plasticity as shown in Figure 6.

3. The variances within and among operators in the moisture tension method was found to be very small for both the observed values and the values estimated by using any prediction equations shown.
4. The data indicate that it should be possible to apply the moisture tension test using just two pressures (3 psi and 20 psi) or a soil to estimate its consistency limits regardless of its soil textural classification.
5. The moisture tension method may be a useful tool for estimating grain size composition of soils. The need for further study on this is suggested.
6. Even though there is little chance in this method for operator error, additional attention should be directed to standardization methods of sample preparation.
7. The results of the time factor study suggest it may not be practical to use higher pressures to achieve moisture equilibrium more quickly.

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APPENDIX A

Test Data

Table A-1. Summary of Liquid Limit Values

Operator Soil No.	Liquid Limit (Percent)					
	A	B	C	D	E	F
1			46.0 46.9 47.6 50.7 56.0	48.4 49.6 50.3 50.6 53.0	51.0	48.0
2	43.0	38.5				47.8
4	27.4 28.3 27.7 26.6 29.3	27.8 28.4 28.5 26.7 28.5			31.1	34.8
5	25.5 24.7	26.0 24.3				24.5
6	28.9 28.6 26.6 26.2 26.8	26.7 27.0 28.5 27.5 25.6	31.3 28.7 31.1 28.4 28.3	26.2 27.5 28.9 27.9 27.6		32.2
7		26.3				27.7
8			28.0 27.4 27.8 28.0 28.2	31.7 29.2 29.8 30.4 28.9	27.5	26.5
9	30.4					30.5
10	21.5					18.7

Table A-1, cont.

Operator Soil No.	Liquid Limit (Percent)					
	A	B	C	D	E	F
11	20.8 20.6 20.5 20.2 19.5	19.6 19.1 20.0 20.3 20.1			20.8	20.8
12	23.5	22.2			21.4	22.6
13	41.7 41.3 41.1 44.4 42.5	41.3 39.5 43.9 40.9 41.4				39.2
14	18.4					17.7
15	25.8	20.3				19.5
16						N.P.
17	18.6 19.2 19.3 19.5 18.9	19.0	21.0 19.3 19.4 19.6 19.0	19.3 20.1 19.2 19.6 19.2	18.4	18.6
18	22.0 25.3 23.9 23.1 22.8	22.9			20.5	23.0
19	30.8	27.6			29.4	24.8
20	N.P.					N.P.
21	N.P.					N.P.
22	24.9	22.7				20.9
23	N.P.					N.P.
24	N.P.					N.P.

Table A-1, cont.

Operator Soil No.	Liquid Limit (Percent)					
	A	B	C	D	E	F
25	N.P.					N.P.
26	N.P.					N.P.
27	N.P.					N.P.
28			65.7 56.8 55.0 54.8 61.0	57.6 57.4 56.3 58.2 58.2		

Table A-2. Summary of Plastic Limit Values

Operator Soil No.	Plastic Limit (Percent)					
	A	B	C	D	E	F
1			30.7 28.0 29.5 32.7 27.7	27.8 29.8 29.7 26.2 30.5	29.2	25.8
2	28.8	16.8				26.3
4	18.3 15.9 16.1 15.1 12.4	12.0 12.4 12.3 12.0 14.0			14.4	17.9
5	14.9 16.5	12.8 14.3				16.6
6	14.7 11.8 19.3 15.9 17.7	13.7 15.0 12.5 16.6 14.1	19.7 21.1 22.7 20.9 20.6	17.9 17.8 19.1 18.1 19.1		16.3
7		11.9				16.4
8	13.2		17.4 17.1 16.9 16.7 16.0	16.7 16.3 16.1 15.7 14.4	14.0	16.4
9					23.5	25.3
10	N.P.					N.P.

Table A-2, cont.

	Plastic Limit (Percent)					
Operator Soil No.	A	B	C	D	E	F
11	15.5	11.8			14.8	15.5
	12.7	10.6				
	14.7	10.8				
	12.2	13.3				
	13.3	11.8				
12	14.8	13.5			17.7	20.4
13	35.1	30.2			31.5	
	33.8	26.8				
	36.5	28.6				
	33.3	31.2				
	29.7	29.2				
14	N.P.					N.P.
15	16.7	10.1				13.9
16						N.P.
17	12.5	11.0	15.3	14.0	13.9	13.4
	13.1		14.6	14.0		
	12.3		14.3	13.4		
	14.8		14.6	14.0		
	12.9		15.9	14.7		
18	19.1	11.4			14.7	15.2
	15.2					
	15.2					
19	21.2	14.0			18.2	
20	N.P.					N.P.
21	N.P.					N.P.
22	18.0	13.8				17.0
23	N.P.					N.P.
24	N.P.					N.P.

Table A-2, cont.

	Plastic Limit (Percent)					
Operator Soil No.	A	B	C	D	E	F
25	N.P.					N.P.
26	N.P.					N.P.
27	N.P.					N.P.
28			28.5 27.7 30.4 30.3 29.6	29.2 28.7 29.9 27.1 29.0		

Table A-3. Summary of Test Results for the Artificially Prepared Soils

Test Results Soil No.	Standard Test		M. T. M.	
	L.L. (%)	P.L. (%)	WC ₃ [*] (%)	WC ₂₀ ^{**} (%)
1 - 75	41.5	24.3	38.64	21.66
1 - 50	31.0	19.8	31.09	17.07
1 - 25	22.2	15.7	22.78	10.75
1 - 15	19.8	N.P.	17.70	8.66
7 - 75	24.3	13.5	22.00	13.40
7 - 50	21.3	14.5	17.32	10.16
7 - 25	19.0	N.P.	12.97	7.46
8 - 75	25.4	14.0	24.03	13.84
8 - 50	21.4	15.5	18.38	10.89
8 - 25	19.1	N.P.	14.32	8.15
9 - 100	32.6	23.5	35.06	15.31
9 - 75	27.3	19.9	29.67	12.87
9 - 50	21.5	16.3	24.40	10.18
9 - 25	N.P.	N.P.	18.69	7.72
10 - 75	18.3	N.P.	25.03	9.11
10 - 50	16.0	N.P.	19.19	7.66
10 - 25	15.0	N.P.	13.66	6.23
11 - 75	20.0	14.0	20.42	12.53
11 - 50	18.0	14.6	17.98	9.93
11 - 25	15.7	N.P.	13.30	7.84
15 - 75	20.0	14.0	20.12	13.01
15 - 50	18.6	14.7	17.68	10.46
15 - 25	16.8	N.P.	13.16	8.24
17 - 75	19.4	14.1	21.02	11.70
17 - 50	18.1	14.8	18.88	9.55
17 - 25	17.6	N.P.	13.84	7.73
30 - 75	40.0	23.0	35.53	24.40
30 - 50	31.8	19.5	30.03	17.83
30 - 25	24.5	15.8	19.70	11.52
30 - 15	21.3	N.P.	15.33	8.74

*Moisture content @ 3 psi using moisture tension device

**Moisture content @ 20 psi using moisture tension device

Table A-6. Water Content by Moisture Tension Test

WC₃, Operator I

Date Soil No.	Dec 18 (%)	Dec 19 (%)	Dec 20 (%)	Average (%)	Standard Deviation (%)
1	43.03	46.06	43.69	44.26	1.59
4	30.80	33.70	31.19	31.90	1.57
7	27.83	27.77	26.08	27.23	0.99
8	26.65	26.57	26.30	26.51	0.18
9	35.80	39.65	35.47	36.97	2.32
10	29.49	31.11	28.99	29.86	1.11
11	21.88	24.32	22.51	22.90	1.27
12	20.90	22.95	22.61	22.15	1.10
14	22.97	25.60	25.75	24.77	1.56
15	23.66	24.82	24.62	24.37	0.62
16	22.82	21.86	25.61	23.43	1.95
17	20.95	23.57	23.01	22.51	1.38
18	21.11	19.26	22.23	20.87	1.50
19	16.98	16.26	15.49	16.24	0.75
20	14.81	13.93	14.17	14.30	0.45
21	9.07	9.34	9.36	9.26	0.16
22	24.99	25.61	25.31	25.30	0.31
23	7.33	7.12	8.13	7.53	0.53
24	3.68	4.27	5.14	4.36	0.73
26	6.44	4.86	5.54	5.61	0.79
27	9.25	7.71	9.25	8.74	0.89
28	45.74	45.62	43.27	44.88	1.39
Average Standard Deviation					1.05

Table A-7. Water Content by Moisture Tension Test

WC₂₀, Operator I

Date Soil No.	Dec 18 (%)	Dec 19 (%)	Dec 20 (%)	Average (%)	Standard Deviation (%)
1	28.02	30.07	29.92	29.34	1.14
4	18.14	18.73	19.04	18.64	0.46
7	18.26	17.46	16.68	17.47	0.79
8	16.24	16.57	17.25	16.69	0.52
9	15.71	15.56	15.36	15.54	0.18
10	14.34	12.67	12.23	13.08	1.11
11	15.25	16.95	15.57	15.92	0.90
12	12.28	13.20	12.76	12.75	0.46
14	10.33	10.83	10.76	10.64	0.27
15	17.36	16.49	17.02	16.96	0.44
16	13.85	10.15	11.38	11.79	1.88
17	14.17	15.03	14.29	14.50	0.47
18	11.71	10.76	12.91	11.79	1.08
19	11.51	10.79	12.47	11.59	0.84
20	7.52	6.20	6.05	6.59	0.81
21	5.45	5.08	5.85	5.46	0.39
22	13.18	13.94	14.98	14.03	0.90
23	4.89	3.82	4.86	4.52	0.61
24	2.51	2.82	3.34	2.89	0.42
26	3.73	3.29	3.59	3.54	0.22
27	5.11	4.04	5.40	4.85	0.72
28	32.66	31.91	32.20	32.26	0.38
Average Standard Deviation					0.68

Table A-8 Water Content by Moisture Tension Test

WC₃, Operator J

Date Soil No.	Jan 24 (%)	Jan 27 (%)	Jan 28 (%)	Average (%)	Standard Deviation (%)
1	43.94	45.39	44.37	44.57	0.74
4	30.12	31.64	27.18	29.65	2.26
7	24.46	29.82	27.34	27.21	2.68
8	26.63	26.84	26.54	26.67	0.15
9	35.10	35.35	36.02	35.49	0.48
10	28.63	30.06	28.46	29.05	0.88
11	22.88	23.62	22.63	23.04	0.51
12	22.03	18.68	23.03	21.25	2.28
14	23.96	22.03	22.29	22.76	1.05
15	22.65	23.64	20.91	22.40	1.38
16	23.90	23.22	22.13	23.08	0.89
17	22.13	24.10	20.07	22.10	2.02
18	19.32	19.15	19.32	19.26	0.10
19	17.33	17.54	18.17	17.68	0.44
20	12.80	13.00	14.01	13.28	0.65
21	9.33	8.22	9.64	9.06	0.75
22	24.15	26.18	24.36	24.90	1.12
23	6.86	6.45	8.25	7.19	0.94
24	4.56	3.79	3.83	4.06	0.43
26	4.89	4.83	5.28	5.00	0.24
27	9.09	8.66	8.40	8.72	0.35
28	41.28	46.95	45.59	44.61	2.96
Average Standard Deviation					1.06

Table A-9. Water Content by Moisture Tension Test

WC₂₀, Operator J

Date Soil No.	Jan 24 (%)	Jan 27 (%)	Jan 28 (%)	Average (%)	Standard Deviation (%)
1	26.89	26.53	28.11	27.18	0.83
4	16.83	16.91	16.29	16.68	0.34
7	14.69	19.03	16.66	16.79	2.17
8	17.06	17.11	15.51	16.56	0.91
9	14.79	14.64	14.51	14.65	0.14
10	12.17	12.85	11.31	12.11	0.77
11	15.66	15.11	14.48	15.08	0.59
12	12.82	11.74	12.61	12.39	0.57
14	9.56	10.32	9.02	9.63	0.65
15	16.37	15.72	16.00	16.03	0.33
16	12.04	11.09	11.86	11.66	0.50
17	12.74	14.12	12.72	13.19	0.80
18	11.37	11.77	10.82	11.32	0.48
19	11.73	11.39	12.19	11.77	0.40
20	4.99	5.00	5.14	5.04	0.08
21	5.30	4.87	4.86	5.01	0.25
22	13.79	15.10	13.07	13.99	1.03
23	4.31	3.80	3.98	4.03	0.26
24	2.87	2.67	2.66	2.73	0.12
26	5.43	3.07	3.48	3.99	1.26
27	4.42	3.43	4.38	4.08	0.56
28	30.24	32.43	33.03	31.90	1.47
Average Standard Deviation					0.66

Table A-10. Effect of Plate on Test Results

Pressure	Plate No.	5526	5520	5508	5518	5525	5527	Average
	Soil No.							
0.4 psi	1	56.31	60.70	55.40	56.97	57.78	57.45	
		56.64	60.45	55.90	57.98	57.36	57.82	
		56.08	60.66	56.05	56.97	57.47	58.19	
		Ave	56.34	60.60	55.79	57.31	57.54	57.82
	28	57.40	59.79	56.64	57.63	56.97	57.13	
		55.64	59.92	56.47	57.08	56.20	55.77	
		54.57	59.05	55.19	57.18	56.32	56.97	
		Ave	55.87	59.59	56.10	57.30	56.50	56.62
	7	33.85	35.23	31.71	31.29	34.22	33.68	
		33.64	36.03	31.48	32.21	34.94	35.18	
		33.87	34.29	34.49	33.46	34.46	35.16	
		Ave	33.79	35.18	32.56	32.32	34.53	34.67
1.0 psi	1	54.02	56.10	53.42	55.70	56.51	55.39	
		54.40	55.65	53.62	55.74	56.90	55.32	
		54.40	55.86	53.97	55.75	56.52	54.93	
		Ave	54.27	55.87	53.67	55.73	56.64	55.21
	28	52.17	53.75	52.69	54.74	52.78	54.24	
		52.38	53.87	53.09	54.01	53.02	54.37	
		52.15	52.86	53.82	54.81	54.99	54.14	
		Ave	52.23	53.49	53.20	54.52	53.60	54.25
3.0 psi	8				24.36	25.31	26.20	
					24.44	25.38	26.25	
					24.55	25.66	27.55	
					24.45	25.45	26.67	25.52
4.0 psi	8	24.27	23.56	24.19				
		24.39	24.01	24.35				
		25.03	24.21	24.39				
		Ave	24.56	23.93	24.31			24.27

Table A-11. Effect of Time and Pressure on Water Content

(a) Soil 2

Time (hr) Pressure (psi)	1	2	4	13,14,16*	24	36	48
1.0	46.79	45.08	44.16	45.68	41.17	42.87	42.86
psi	47.83	46.35	44.79	46.11	43.15	43.19	43.20
Ave.	47.31	45.72	44.48	45.90	42.16	43.03	43.03
2.0	45.38	42.05	40.00	41.59	42.05	40.89	41.84
psi	56.10	42.94	41.39	42.21	41.27	41.89	41.89
Ave.	50.74	42.50	40.70	41.59	42.13	41.09	41.87
4.0	36.57	33.04	33.99	38.51	33.82	33.48	38.31
psi	37.03	33.35	34.49	38.57	33.97	33.52	39.32
Ave.	36.80	33.20	34.24	38.54	33.90	33.50	38.82

*14 hrs for 1.0 psi, 13 hrs for 2.0 psi and 16 hrs for 4.0 psi

(b) Soil 3

Time (hr) Pressure (psi)	1	2	4	13,14,16*	24	36	48
1.0	49.61	42.92	42.24	44.79	44.39	41.85	39.60
psi	55.90	43.51	42.94	45.05	46.94	42.22	41.84
Ave.	52.76	43.22	42.59	44.92	45.67	42.07	40.72
2.0	47.54	40.42	39.59	37.97	42.45	41.80	39.48
psi	52.82	40.83	39.85	39.98	43.74	41.95	40.83
Ave.	50.18	40.86	39.72	38.98	43.10	41.88	40.16
4.0	36.23	36.30	32.34	34.72	36.12	31.46	36.10
psi	37.92	36.31	34.13	35.15	37.28	31.82	36.15
Ave.	37.08	36.31	33.24	34.94	36.70	31.64	36.13

*14 hrs for 1.0 psi, 13 hrs for 2.0 psi and 16 hrs for 4.0 psi

Table A-11, cont.

(c) Soil 5

Time (hr) Pressure (psi)	1	2	4	13,14,16*	24	36	48
1.0	27.23	24.96	27.23	25.60	24.73	24.12	24.07
psi		25.52	27.62	26.21	25.26	24.29	24.29
Ave.	27.23	25.24	27.43	25.91	25.00	24.46	24.18
2.0	28.01	26.19	25.93	25.07	26.74	25.90	26.49
psi	29.18	27.38	26.01	25.84	27.45	26.33	26.56
Ave.	28.60	26.79	25.97	25.46	27.10	26.12	26.53
4.0	24.67	14.34	15.58	23.85	16.24	15.96	23.81
psi	24.55	15.90	16.04	24.05	17.38	16.51	23.85
Ave.	24.61	15.12	15.81	23.95	16.81	16.24	23.83

*14 hrs for 1.0 psi, 13 hrs for 2.0 psi and 16 hrs for 4.0 psi

(d) Soil 6

Time (hr) Pressure (psi)	1	2	4	13,14,16*	24	36	48
1.0	33.33	30.53	32.31	30.25	30.84	31.28	31.19
psi	36.26	32.00	32.88	32.62	31.56	21.63	31.32
Ave.	34.80	31.27	32.60	31.44	31.20	31.46	31.26
2.0	32.19	29.30	28.20	29.10	29.62	29.38	30.12
psi	37.40	30.25	28.56	29.29	30.03	30.06	30.72
Ave	34.80	29.78	28.38	29.20	29.83	29.72	30.42
4.0	26.05	21.84	17.34	25.99	25.35	16.88	24.77
psi	27.11	22.76	18.20	26.37	26.60	17.55	25.39
Ave	26.58	22.30	17.77	26.18	25.98	17.22	25.08

*14 hrs for 1.0 psi, 13 hrs for 2.0 psi and 16 hrs for 4.0 psi

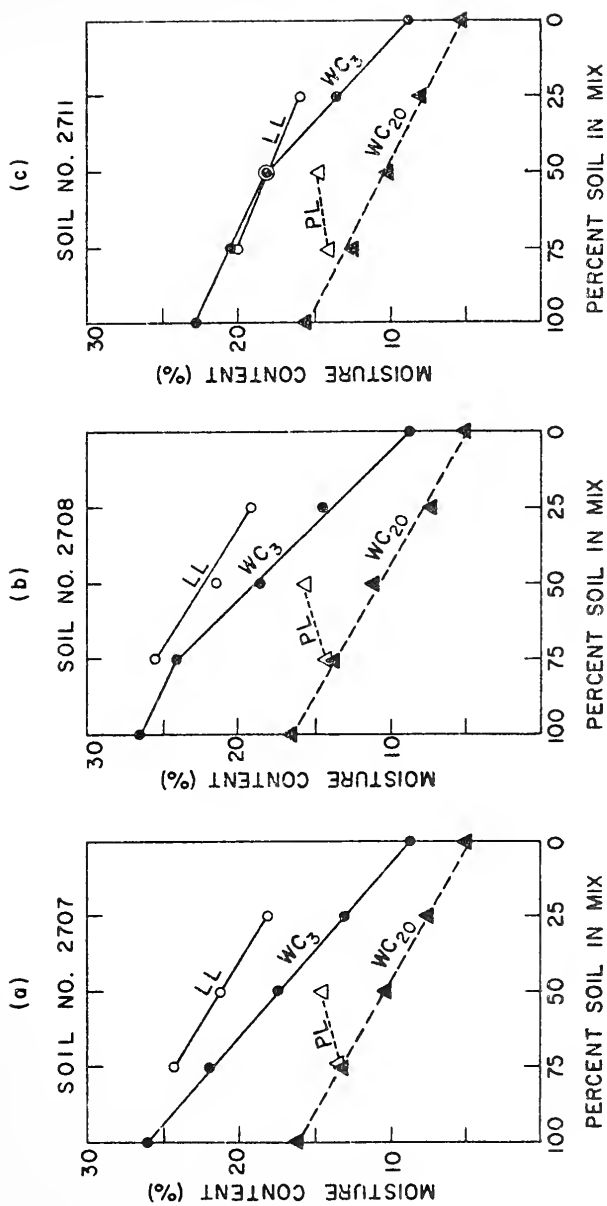


FIGURE A-1 EFFECT OF PERCENT SOIL IN THE MIX ON TEST VALUES FOR THE ARTIFICIALLY PREPARED SOILS

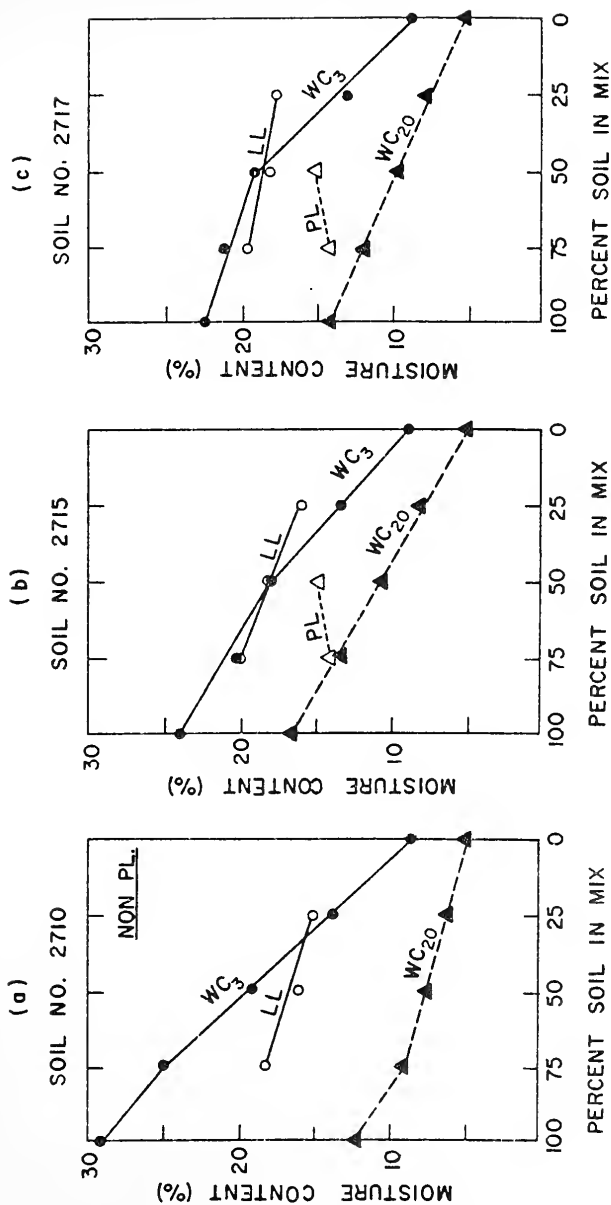


FIGURE A-2 EFFECT OF PERCENT SOIL IN THE MIX ON TEST VALUES FOR THE ARTIFICIALLY PREPARED SOILS

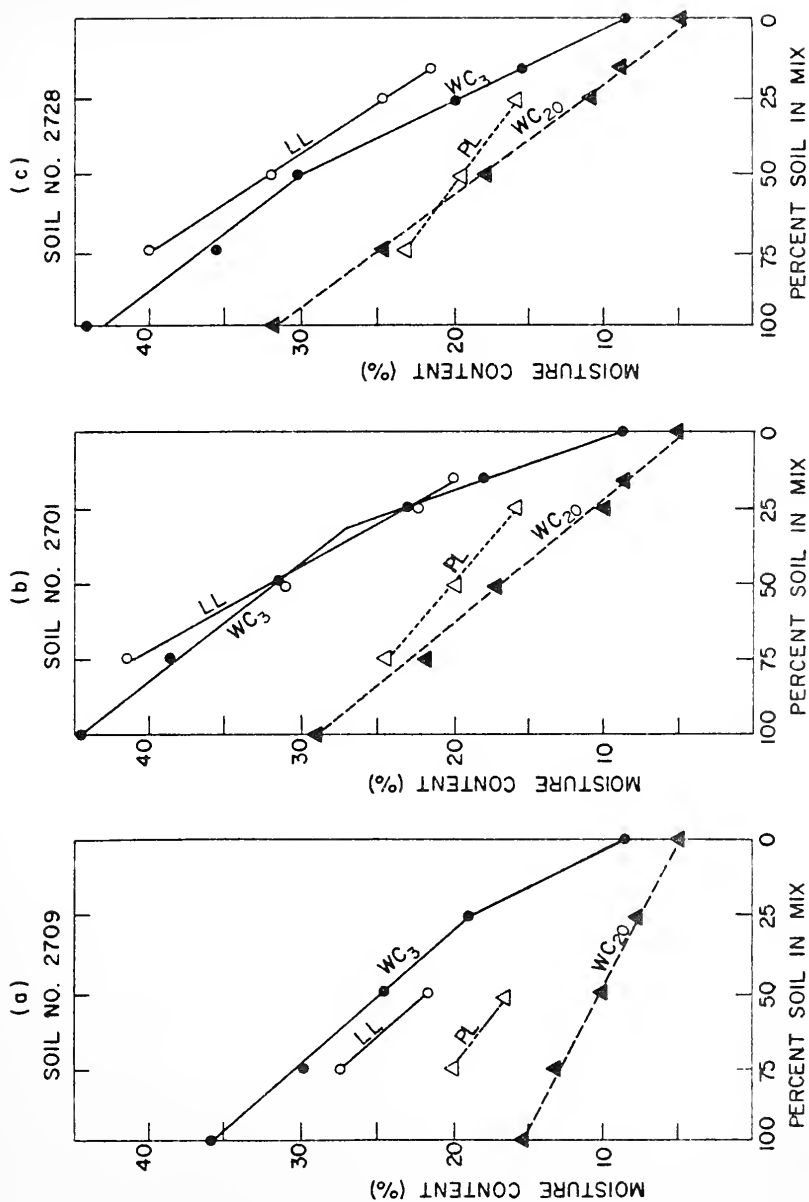


FIGURE A-3 EFFECT OF PERCENT SOIL IN THE MIX ON TEST VALUES FOR THE ARTIFICIALLY PREPARED SOILS

APPENDIX B

Tests for Operator Effect

Table B-1. Two-way ANOVA for LL

Case	Source	S.S.	D.F.	M.S.	F	Critical F
1	Operator	13.76	3	4.59	2.71	9.28*
	Soil	596.32	1	596.32		
	Ope · Soil	5.08	3	1.69		
	Error	27.00	28	0.96		
2	Operator	1.85	1	1.85	6.23	6.61*
	Soil	622.61	5	524.52		
	Ope · Soil	1.47	5	0.29		
	Error	43.09	38	1.13		
3	Operator	0.02	1	0.02	0.00249 1/F = 402	5625**
	Soil	10,513.72	4	2,628.43		
	Ope · Soil	26.05	4	6.51		
	Error	188.11	40	4.70		

* $\alpha = 0.05$ ** $\alpha = 0.01$ Model: $Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \epsilon_{(ij)k}$

Table B-2. Two-way ANOVA for PL

Case	Source	S.S.	D.F.	M.S.	F	Critical F
1	Operator	110.00	3	36.66	7.64	9.28*
	Soil	142.09	1	142.09		
	Ope · Soil	14.39	3	4.80		
	Error	55.34	28	1.98		
2	Operator	125.61	1	125.61	23.77	16.26**
	Soil	2,547.81	5	509.56		
	Ope · Soil	26.42	5	5.28		
	Error	232.62	35	6.65		
3	Operator	45.70	1	45.70	2.92	7.71*
	Soil	2,080.23	4	520.06		
	Ope · Soil	62.70	4	15.68		
	Error	316.43	40	7.91		
4	Operator	60.21	2	30.10	4.42	19.00*
	Soil	145.20	1	145.20		
	Ope · Soil	13.61	2	6.81		
	Error	46.00	24	1.91		

* $\alpha = 0.05$ ** $\alpha = 0.01$ Model: $Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + \epsilon_{(ij)k}$

Table B-3. Tests Between Two Operators, LL

Case	$q^{(1)}$	Critical q	$\bar{D}^{(2)}$	$S_D^2(3)$	$t^{(4)}$	critical t
4	0.50	0.89*	3.05	0.82	3.38	$t(3) = 5.81^{**}$
5	0.54	0.72*	1.98	0.75	2.28	$t(7) = 2.37^*$
6	0.58	0.72*	-0.68	1.15	-0.64	$t(7) = 2.37^*$
7	0.50	0.72*	0.13	0.75	0.14	$t(7) = 2.37^*$

Table B-4. Tests Between Two Operators, PL

Case	$q^{(1)}$	Critical q	$\bar{D}^{(2)}$	$S_D^2(3)$	$t^{(4)}$	critical t
5	0.57	0.89*	4.83	1.80	3.60	$t(3) = 3.18^*$
6	0.51	0.89*	0.18	0.92	0.19	$t(3) = 3.18^*$
7	0.65	0.75*	-4.87	0.88	-5.18	$t(6) = 2.45^*$
8	0.54	0.75*	-0.84	0.26	-1.94	$t(6) = 2.45^*$

* $\alpha = 0.05$ ** $\alpha = 0.01$

- (1) q : is expressed in the following equation for the Q-test for equality of variances.

$$q = \frac{\sum S_j^4}{(\sum S_j^2)^2} \quad S_j \text{ denotes the } j\text{th sample variance.}$$

- (2) \bar{D} = the average difference between the observations by two operators.

- (3) $S_D^2 = S_D^2/n$ n = number of observations.

- (4) $t = \bar{D}/S_D$

APPENDIX C

Input Data for Regression Analysis

Table C-1. Input Data for the all Random Combination Analysis

Soil No.	L.L. (%)	P.L. (%)	Operator (%)	WC ₃ (%)	WC ₂₀ (%)	Operator (%)
1	46.0	27.7	C	43.75	30.64	H
	56.0	32.7	C	43.25	29.72	H
	50.7	30.7	C	43.03	28.02	I
	46.9	28.0	C	43.69	29.92	I
	50.3	29.7	D	43.83	32.66	H
	53.0	30.5	D	47.07	28.89	H
	48.4	26.2	D	44.37	28.11	J
	49.6	27.8	D	43.94	26.89	J
	50.6	29.8	D	44.43	28.89	H
	51.0	29.2	E	46.06	30.07	I
	48.0	25.8	F	45.39	26.53	J
2		28.8	A	43.64	27.72	H
	47.8	26.3	F	43.16	29.25	H
4	27.7	15.9	A	31.64	16.91	J
	26.6	12.4	A	31.19	19.04	I
	27.4	15.1	A	27.73	17.54	H
	28.3	16.1	A	30.80	18.14	I
	29.3	18.3	A	30.96	16.64	H
	26.7		B	28.78	17.62	H
	28.5		B	33.70	18.73	I
	28.4		B	30.12	16.83	J
	27.8		B	28.59	18.12	H
	28.5		B	27.18	16.29	J
	31.1	14.4	E	28.07	17.66	H
5	24.5	16.6	A	27.23	15.38	H
	24.7	14.9	A	27.81	14.51	H
	24.3		B	26.93	15.87	H
	26.0		B	25.96	14.74	H
	25.5	16.6	F	28.50	15.47	H

Table C-1, cont.

Soil No.	L.L. (%)	P.L. (%)	Operator (%)	WC ₃ (%)	WC ₂₀ (%)	Operator (%)
6	27.5	17.7	A	24.93	15.27	H
	27.9	19.1	D	24.47	15.86	H
	25.6	16.3	F	22.05	14.72	H
7	26.3		A	26.08	16.68	I
	27.7	16.4	F	28.23	16.79	H
8	28.0	16.9	C	25.21	15.42	H
	27.4	16.0	C	26.54	15.51	J
	28.0	17.1	C	26.84	17.11	J
	28.2	17.4	C	26.30	17.25	I
	31.7	16.7	D	28.16	15.96	H
	29.8	16.1	D	27.15	16.09	H
	29.2	15.7	D	24.54	15.93	H
	30.4	16.3	D	26.57	16.57	I
	28.9	14.4	D	25.25	16.03	H
	27.5	14.0	E	26.65	16.24	I
	26.5	16.4	F	26.63	17.06	J
9	30.4	25.3	A	35.47	15.93	H
	30.5	23.5	F	35.47	15.36	I
10	21.5		A	29.49	14.34	I
	18.7		F	31.11	12.67	I
11	20.5	13.3	A	22.88	15.66	J
	20.6	14.7	A	22.63	14.48	J
	20.8	15.5	A	21.88	15.25	I
	20.2	12.2	A	21.57	14.87	H
	20.3	12.7	A	22.95	14.96	H
	19.1		B	24.32	16.95	I
	20.3		B	21.42	15.32	H
	20.1		B	23.62	15.11	H
	20.0		B	21.24	15.48	H
	20.8	14.8	E	22.81	15.37	H
	20.8	15.5	F	22.51	15.57	I

Table C-1, cont.

Soil No.	L.L. (%)	P.L. (%)	Operator (%)	WC ₃ (%)	WC ₂₀ (%)	Operator (%)
12	23.5	14.8	A	22.45	13.30	H
	22.2		B	18.68	11.74	J
	21.4		E	22.95	13.20	I
	22.6		F	22.40	11.99	H
14	18.4		A	24.85	10.00	H
	17.7		F	25.75	10.76	I
15	25.8	16.7	A	24.82	16.49	I
	20.3		B	23.64	15.72	J
	19.5		F	22.65	16.37	J
17	18.9	12.5	A	22.13	12.74	J
	19.3		A	22.52	13.90	H
	19.4		C	20.95	14.17	I
	21.0		C	22.21	14.56	H
	19.3		C	21.71	14.38	H
	19.6		D	24.10	14.12	J
	20.1		D	21.25	14.24	H
	19.2		D	22.22	14.35	H
	19.3		D	20.07	12.72	J
	18.4		E	23.57	15.07	I
	19.0		F	23.01	14.29	I
18	23.9	15.2	A	19.32	11.37	J
	22.8		A	19.32	10.82	J
	25.3		A	23.33	12.78	H
	23.1		A	21.60	12.11	H
	22.2		A	19.26	10.76	I
	22.9		B	23.38	12.79	H
	20.5		E	22.23	12.91	I
	23.0		F	19.15	11.77	J
19	30.8	21.2	A	16.98	11.51	I
	27.6		B	16.35	12.38	H
	29.4		E	15.49	12.47	I
	24.8		F	16.26	10.79	I

Table C-1, cont.

Soil No.	L.L. (%)	P.L. (%)	Operator (%)	WC ₃ (%)	WC ₂₀ (%)	Operator (%)
22	24.9	18.0	A	27.11	15.00	H
	22.7		B	27.60	15.96	H
	20.9	17.0	F	24.99	13.18	I
28	56.8	29.6	C	42.42	29.76	H
	54.8	27.7	C	43.36	30.63	H
	65.7	30.4	C	41.28	30.24	J
	55.0	28.5	C	45.74	32.66	I
	61.0	30.3	C	42.70	31.82	H
	58.2	29.9	D	45.59	33.03	J
	57.4	28.7	D	41.38	32.09	H
	58.2	29.2	D	46.95	32.43	J
	57.6	29.0	D	43.27	32.20	I
	56.3	27.1	D	42.29	30.47	H

Total number of tests for L.L. = 104

Total number of tests for P.L. = 81

Table C-2. Input Data for the Random Pull Analysis

Dep. or Ind. Var. L.L., P.L. WC ₃ , WC ₂₀ Soil No.	Dependent Variable		Independent Variable	
	L.L. (%)	P.L. (%)	WC ₃ (%)	WC ₂₀ (%)
1	50.0	28.9	44.37	28.11
2	43.2	27.6	43.16	29.25
4	28.8	15.7	30.80	18.14
5	25.0	16.0	27.23	15.38
6	28.1	18.3	24.93	15.27
7	27.0	16.4	27.17	16.67
8	28.6	15.9	26.65	16.24
9	30.5	24.4	35.80	15.71
10	20.1	-	30.06	12.85
11	20.2	14.1	22.88	15.66
12	22.4	17.6	20.90	12.28
14	18.1	-	23.96	9.56
15	21.9	15.3	24.82	16.83
17	19.3	14.0	22.22	14.35
18	23.0	15.9	21.11	11.71
19	28.2	19.7	17.54	11.39
22	22.8	17.5	24.15	13.79
28	58.1	29.0	43.36	30.63

Number of Samples for L.L. = 18

Number of Samples for P.L. = 16

APPENDIX D

Coefficients of Variation

Table D-1. Coefficient of Variation, $\frac{S}{\bar{X}} \times 100$ (%)(L.L., P.L., WC₃, WC₂₀)

Observed Value	Standard Test		Moisture Tension	
Soil No.	L.L.	P.L.	WC ₃	WC ₂₀
1	5.6	7.1	2.8	6.0
2	15.2	6.4	1.0	4.0
4	7.8	12.9	6.7	5.0
5	2.9	6.1	3.5	3.7
6	6.2	14.8	6.6	3.7
7	3.7	-	6.5	6.7
8	5.1	8.0	3.8	3.9
9	0.2	5.2	4.3	3.4
10	9.9	-	3.6	8.4
11	2.8	9.6	1.7	4.1
12	3.9	15.9	9.7	5.9
14	2.7	-	5.4	6.0
15	15.7	12.9	6.6	3.9
17	3.1	2.6	5.2	5.1
18	5.9	11.4	5.2	6.9
19	9.2	10.8	7.5	6.8
22	8.8	4.0	5.2	8.0
28	5.5	3.7	4.5	3.5
Average	6.3	8.8	5.0	5.3
Std. Dev.	4.2	4.2	2.1	1.6

Table D-2. Coefficient of Variation, $\frac{S}{\bar{X}} \times 100 (\%)$

(Predicted L.L. Values)

Case	All Combination			Random Pull		
Soil No.	1	2	3	4	5	6
1	8.5	4.4	4.7	8.3	4.2	4.3
2	5.6	1.6	2.8	5.4	1.5	2.6
4	4.6	8.2	5.4	4.3	7.7	4.8
5	2.9	4.0	2.6	2.7	3.7	2.3
6	2.9	6.4	4.3	2.8	5.8	3.7
7	5.9	7.3	6.3	5.6	6.8	5.5
8	3.3	4.2	3.0	3.1	3.9	2.6
9	2.6	6.1	3.0	2.5	5.8	2.7
10	5.0	4.4	4.6	4.6	4.1	4.0
11	3.3	4.0	3.2	3.1	3.7	2.8
12	3.5	8.2	4.8	3.2	7.5	4.6
14	2.6	5.4	3.5	2.4	5.0	2.9
15	3.3	6.5	4.1	3.1	6.0	3.5
17	3.5	4.9	3.7	3.3	4.4	3.1
18	3.8	7.9	5.6	3.5	7.2	4.7
19	3.6	4.7	3.6	3.3	4.2	3.0
22	5.3	5.6	5.4	4.9	5.2	4.6
28	5.1	6.9	5.5	4.9	6.7	5.1
Average	4.2	5.6	4.2	3.8	5.2	3.7
Std. Dev.	1.5	1.8	1.1	1.8	1.6	1.0

Case The model used for calculation

$$1 \quad \hat{LL} = 14.97 + 0.0416 (WC_{20})^2$$

$$2 \quad \hat{LL} = 11.72 + 0.0207 (WC_3)^2$$

$$3 \quad \hat{LL} = 13.10 + 0.0301 (WC_3)(WC_{20})$$

$$4 \quad \hat{LL} = 15.95 + 0.0399 (WC_{20})^2$$

$$5 \quad \hat{LL} = 12.46 + 0.0186 (WC_3)^2$$

$$6 \quad \hat{LL} = 16.03 + 0.0283 (WC_3)(WC_{20})$$

Table D-3. Coefficient of Variation, $\frac{S}{\bar{X}} \times 100 (\%)$
(Predicted P.L. Values)

Case Soil No.	All Combination			Random Pull		
	1	2	3	4	5	6
1	6.8	3.6	3.8	6.3	3.4	3.5
2	4.4	1.3	2.2	4.1	1.2	2.1
4	3.1	6.0	3.8	2.8	5.4	3.4
5	1.9	2.8	1.8	1.6	2.5	1.6
6	1.9	4.3	2.9	1.7	3.8	2.5
7	4.0	5.1	4.3	3.5	4.6	3.8
8	2.2	2.9	2.0	1.9	2.6	1.8
9	1.7	4.7	2.1	1.5	4.3	1.9
11	2.2	2.7	2.1	1.9	2.3	1.9
12	2.1	5.3	3.5	1.9	4.6	3.0
15	2.2	4.4	2.7	2.0	3.9	2.4
17	2.2	3.2	2.4	2.0	2.8	2.1
18	2.3	5.1	3.5	2.0	4.5	3.0
19	2.2	2.9	2.2	1.9	2.4	1.8
22	3.4	3.9	3.6	3.0	3.5	3.1
28	4.1	5.7	4.5	3.8	5.3	4.2
Average	2.7	4.0	1.8	2.6	3.6	2.6
Std. Dev.	1.7	1.3	0.9	1.3	1.2	0.8

Case The model used for calculation

1 $\hat{PL} = 12.09 + 0.0179 (WC_{20})^2$

2 $\hat{PL} = 10.38 + 0.0093 (WC_3)^2$

3 $\hat{PL} = 11.17 + 0.0132 (WC_3)(WC_{20})$

4 $\hat{PL} = 13.35 + 0.0168 (WC_{20})^2$

5 $\hat{PL} = 11.58 + 0.0086 (WC_3)^2$

6 $\hat{PL} = 12.43 + 0.0122 (WC_3)(WC_{20})$

APPENDIX E

Moisture Tension Curves

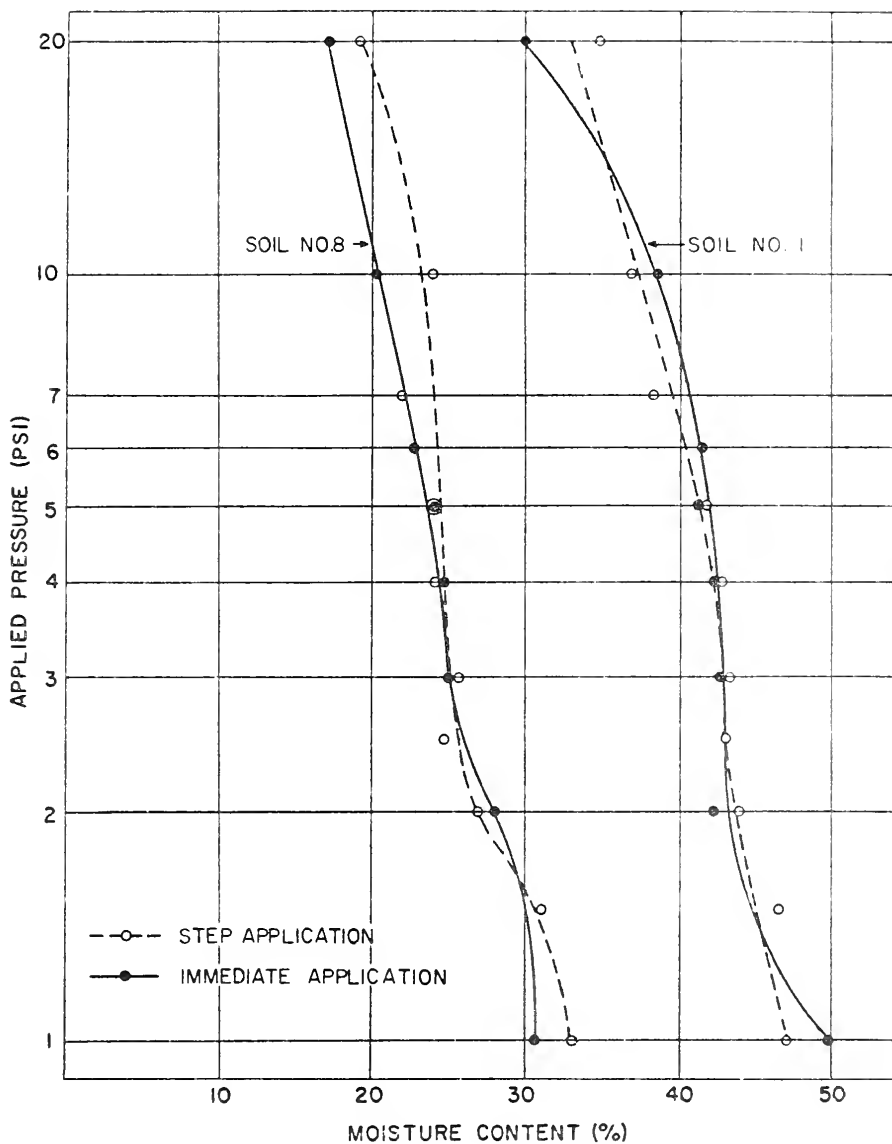


FIGURE E-1 MOISTURE TENSION CURVES DEVELOPED USING TWO PROCEDURES FOR APPLYING PRESSURE

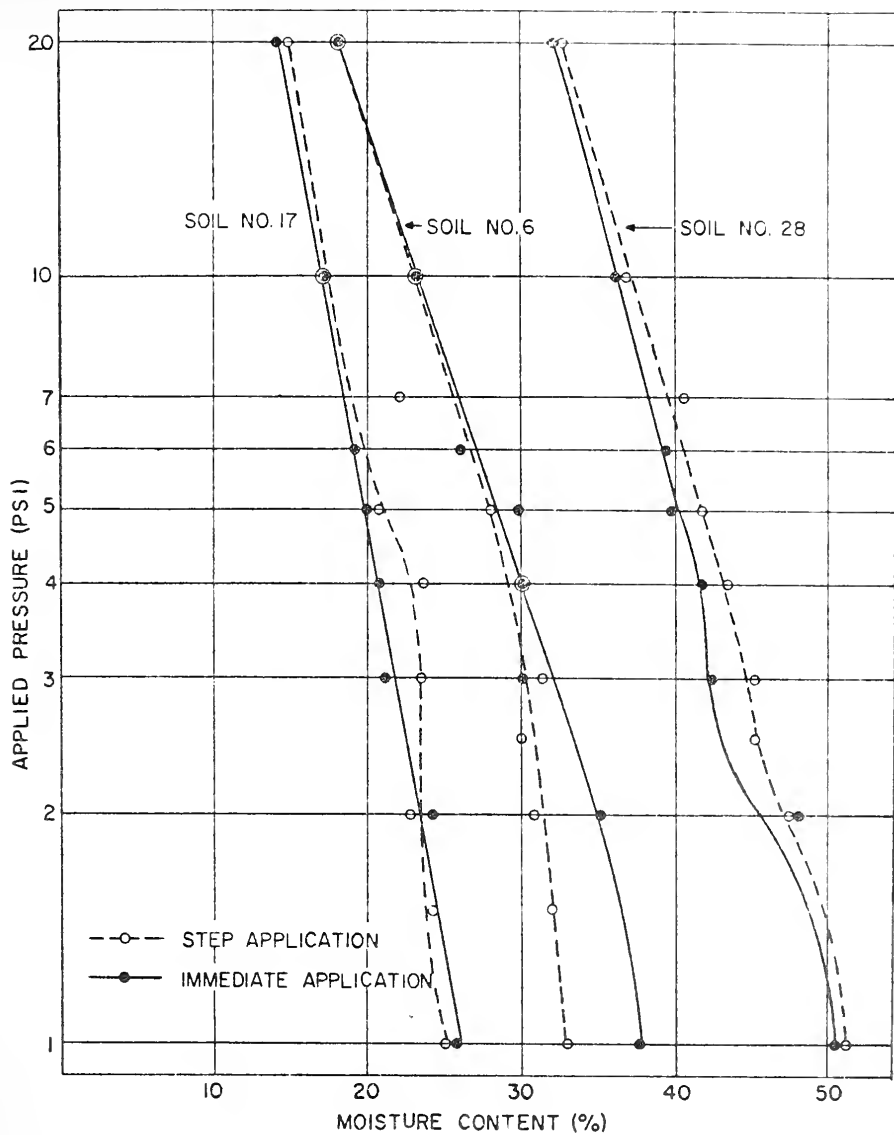


FIGURE E-2 MOISTURE TENSION CURVES DEVELOPED USING TWO PROCEDURES FOR APPLYING PRESSURE

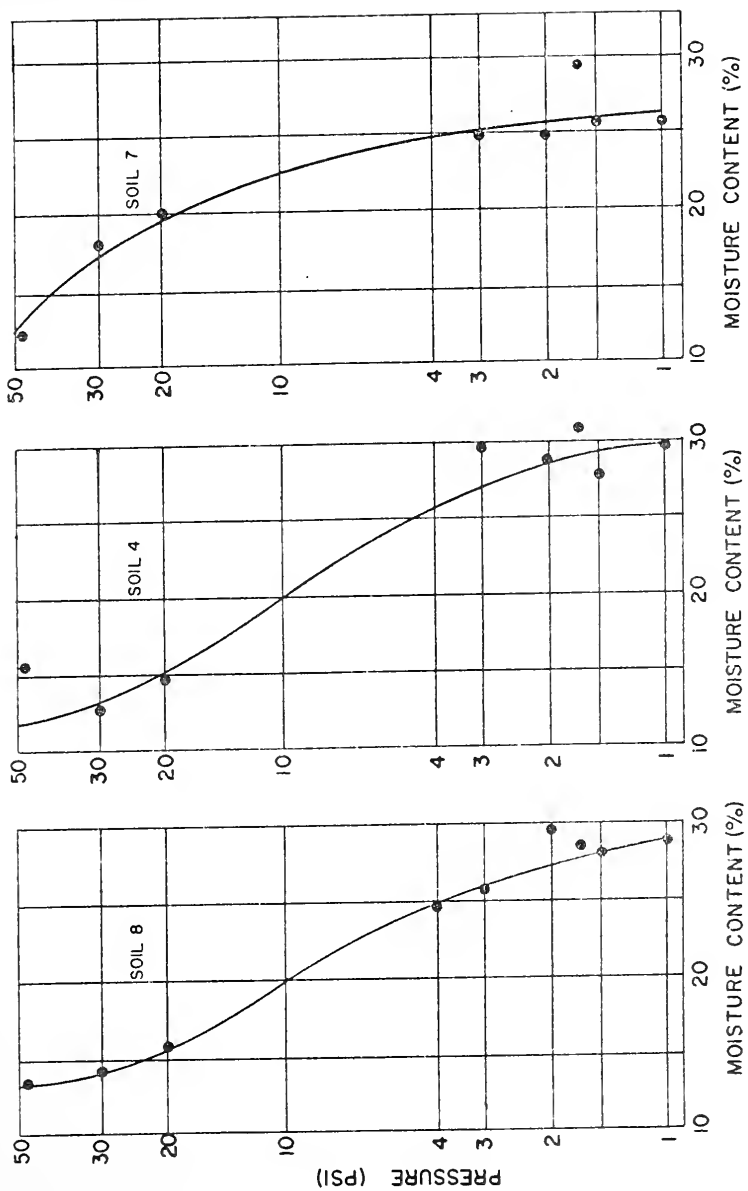


FIGURE E-3 MOISTURE TENSION CURVES FOR THREE CLAYS

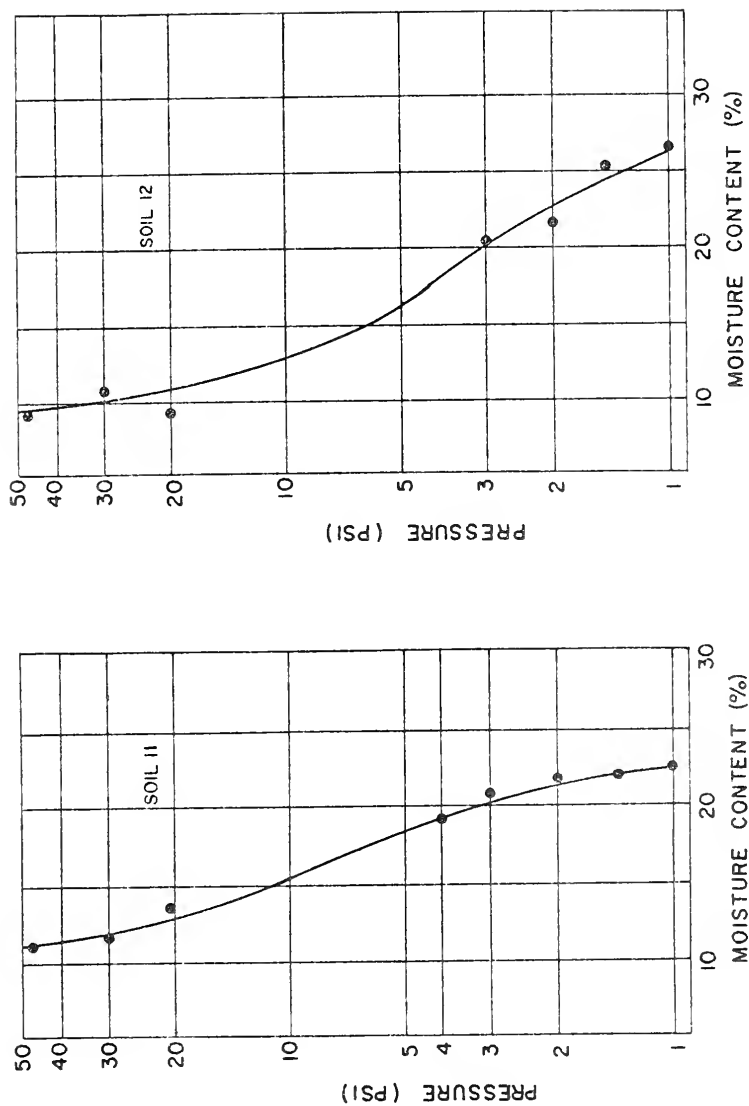


FIGURE E-4 MOISTURE TENSION CURVES FOR TWO CLAY LOAMS (1)

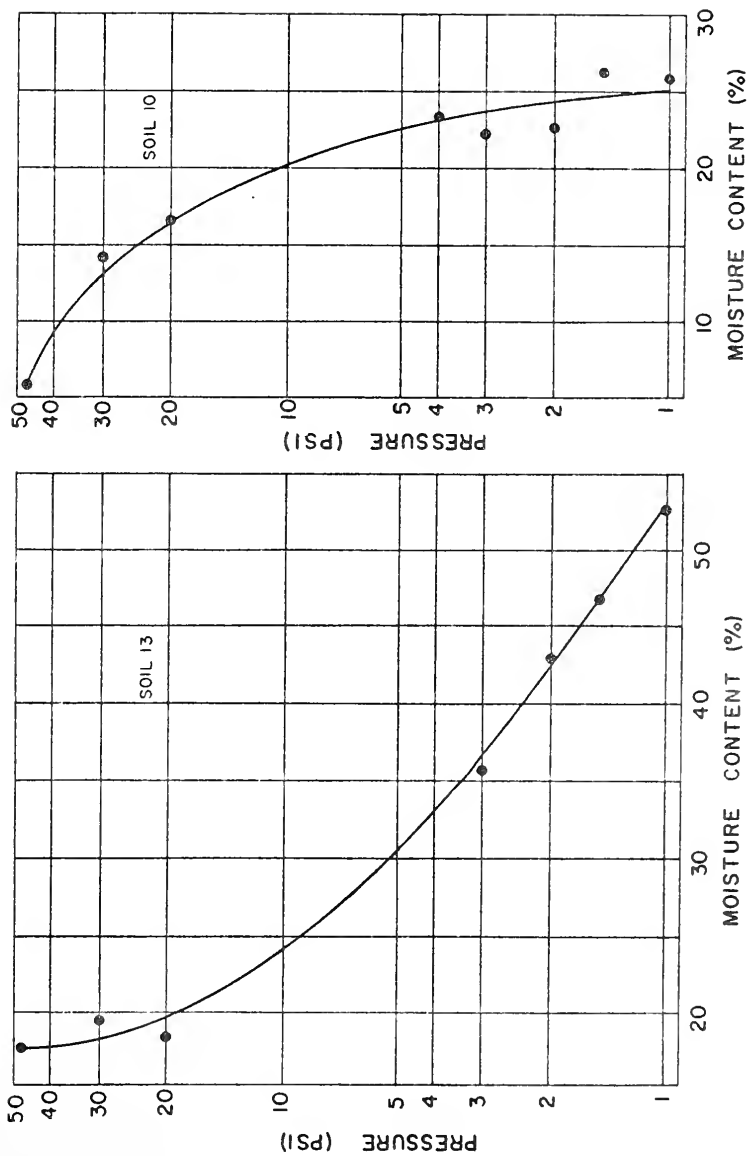


FIGURE E-5 MOISTURE TENSION CURVES FOR TWO CLAY LOAMS (2)

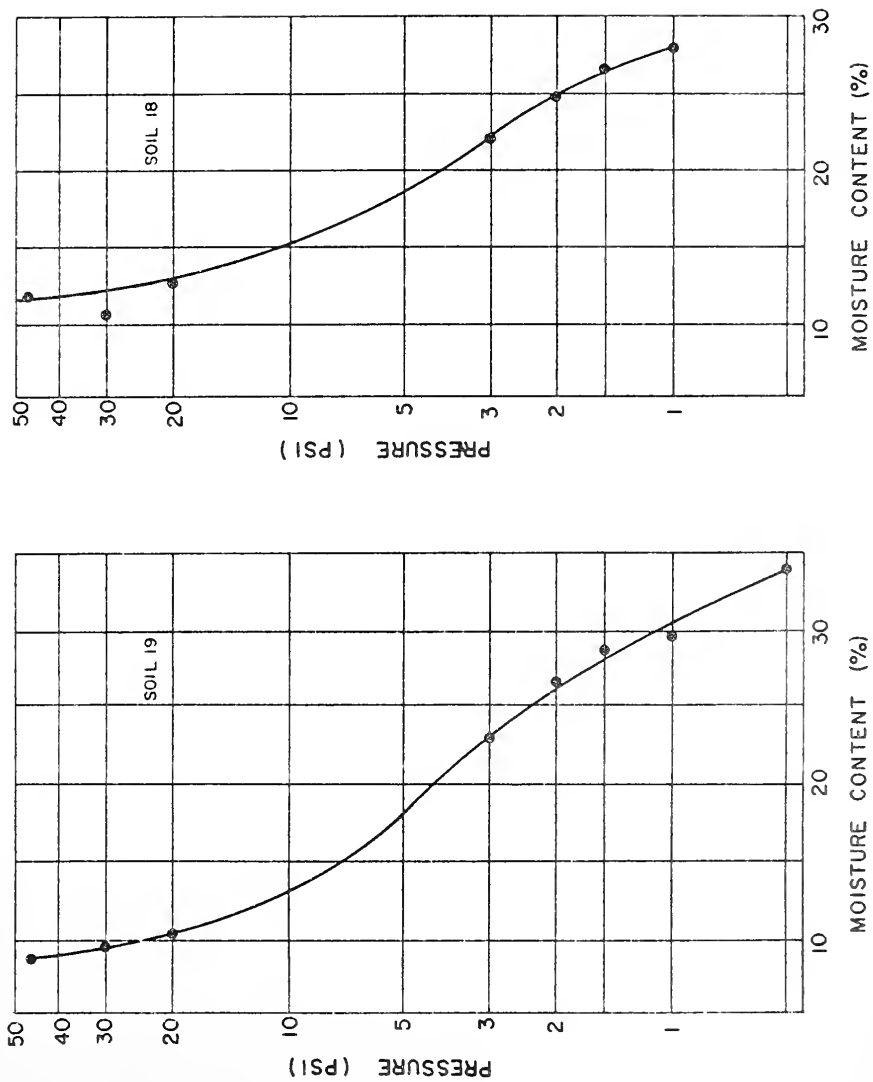


FIGURE E-6 MOISTURE TENSION CURVES FOR TWO SANDY CLAY LOAMS (1)

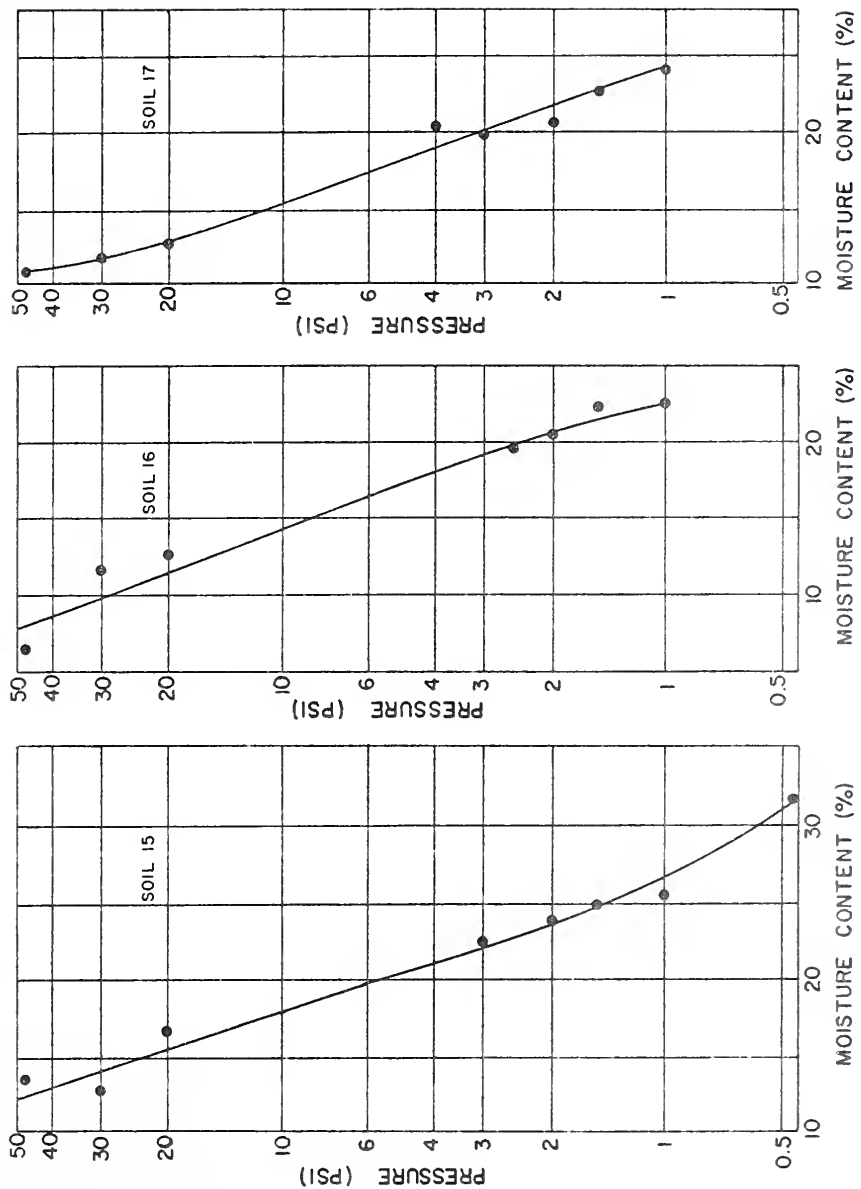


FIGURE E-7 MOISTURE TENSION CURVES FOR THREE SANDY CLAY LOAMS (2)

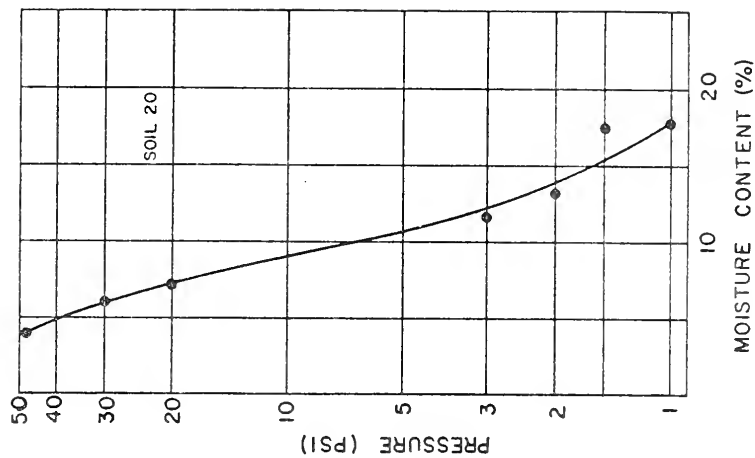


FIGURE E-9 MOISTURE TENSION CURVE
FOR SANDY LOAM

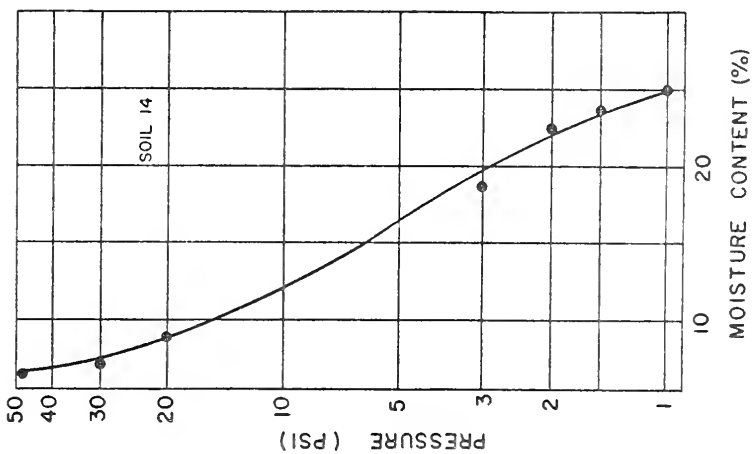


FIGURE E-8 MOISTURE TENSION CURVE
FOR LOAM

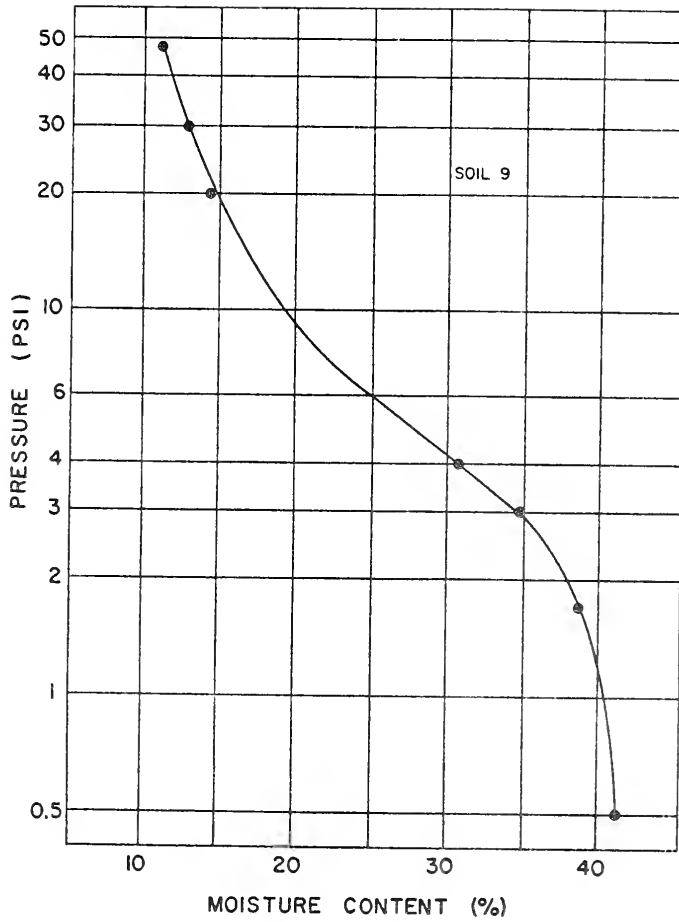


FIGURE E-10 MOISTURE TENSION CURVE FOR SILTY CLAY LOAM

APPENDIX F

Relationships Between Moisture Tension and Soil Composition

Table F-1. Soil Composition for the Passing #40 Portion of the Test Soils (percent in weight)

Natural Soils				Artificially Prepared Soils			
Particle Size Soil No.	#40~0.05 ^{mm} (%)	0.05 ^{mm} ~0.005 ^{mm} (%)	-0.005 ^{mm} (%)	Particle Size Soil No.	#40~0.05 ^{mm} (%)	0.05 ^{mm} ~0.005 ^{mm} (%)	-0.005 ^{mm} (%)
1	7	42	51	1-75	26	32	42
2	7	47	46	1-50	45	22	33
3	13	47	40	1-25	64	11	25
4	41	21	38	1-15	72	7	21
5	41	23	36	7-75	56	8	36
6	37	25	38	7-50	65	6	29
7	48	10	42	7-25	74	3	23
8	48	13	39	8-75	57	10	33
9	14	60	26	8-50	65	7	28
10	29	48	23	8-25	74	4	22
11	37	32	31	9-75	31	45	24
12	41	32	27	9-50	48	31	21
13	43	33	24	9-25	66	15	19
14	46	34	20	10-75	43	36	21

Table F-1, cont.

Natural Soils				Artificially Prepared Soils			
Particle Size Soil No.	#40<0.05 ^{mm} (%)	0.05 ^{mm} ~0.005 ^{mm} (%)	-0.005 ^{mm} (%)	Particle Size Soil No.	#40~0.05 ^{mm} (%)	0.05 ^{mm} ~0.005 ^{mm} (%)	-0.005 ^{mm} (%)
15	44	23	33	10-50	56	24	20
16	52	27	21	10-25	69	13	18
17	47	20	33	11-75	49	24	27
18	54	16	30	11-50	60	17	23
19	71	4	25	11-25	71	9	20
20	66	19	15	15-75	53	18	29
21	75	6	19	15-50	63	12	25
22	37	20	43	15-25	73	7	20
23	81	2	17	17-75	56	15	29
24	87	1	12	17-50	65	11	24
26	73	7	20	17-25	74	6	20
27	83	1	16				

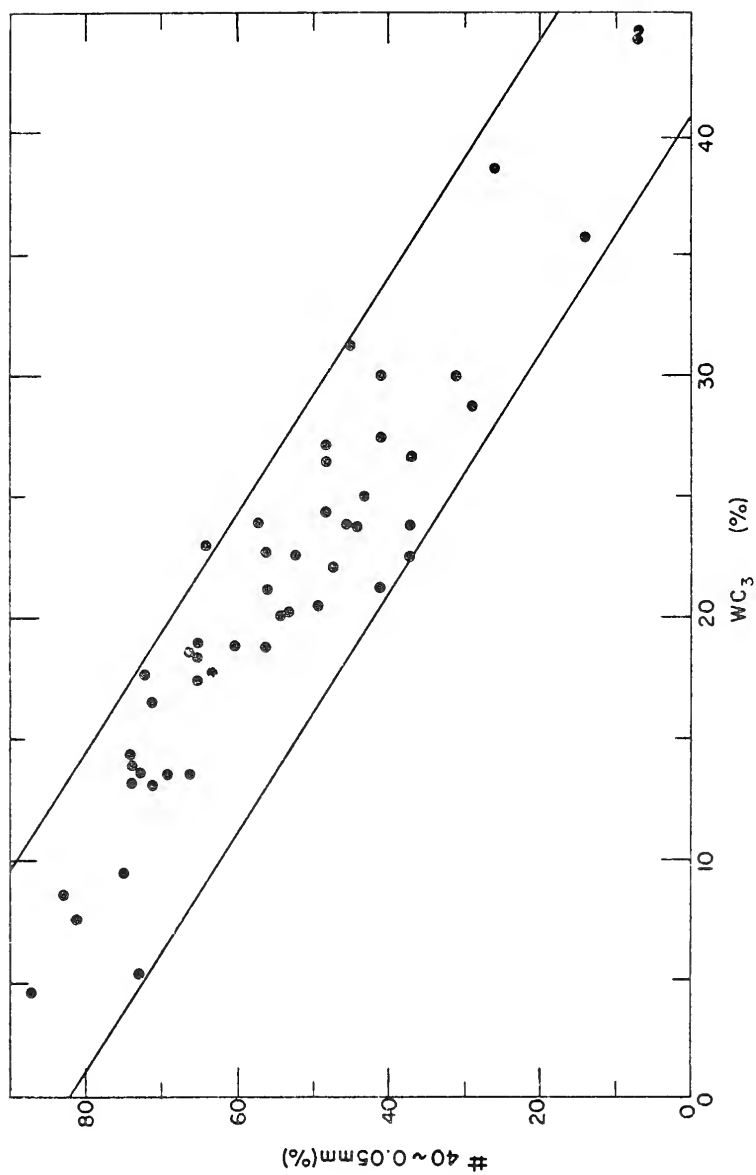


FIGURE F-1 RELATIONSHIP BETWEEN THE PORTION $\#40 \sim 0.05mm$ AND WC_3

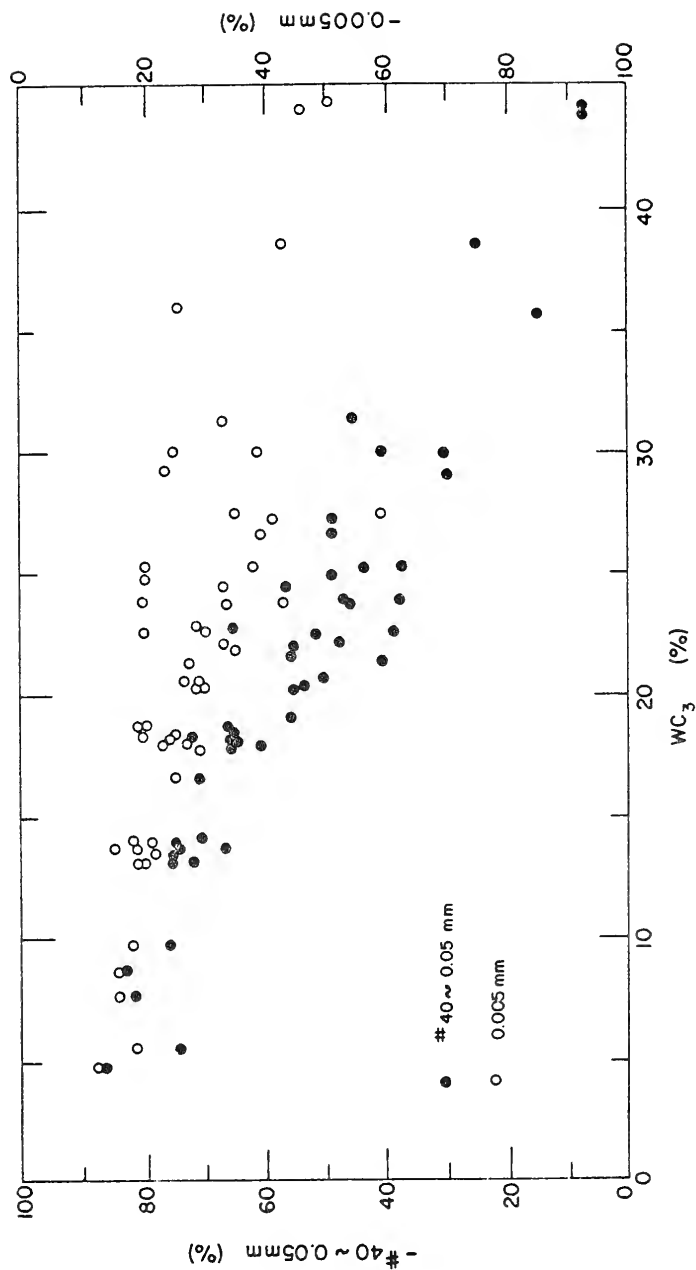


FIGURE F-2 RELATIONSHIP BETWEEN THE PORTION ($- \#40 \sim 0.05 \text{ mm}$ AND -0.005 mm) AND WC_3

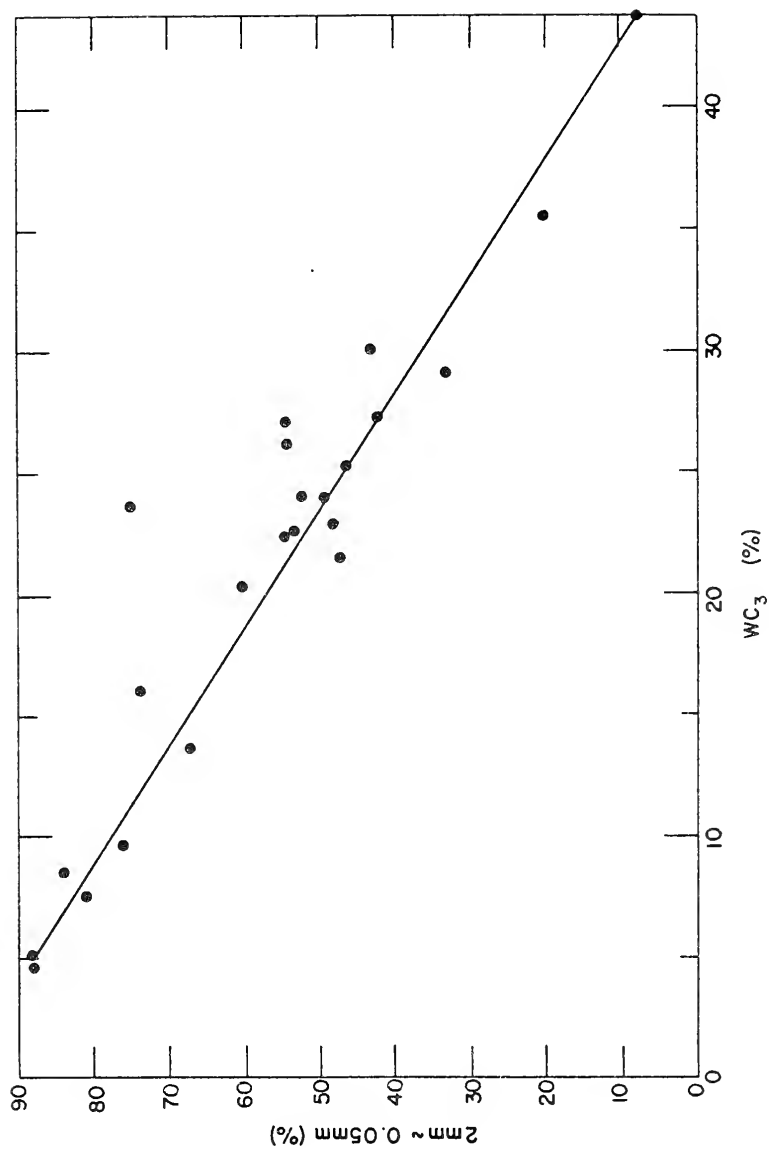


FIGURE F-3 RELATIONSHIP BETWEEN THE PORTION (2mm ~ 0.05mm) AND WC_3

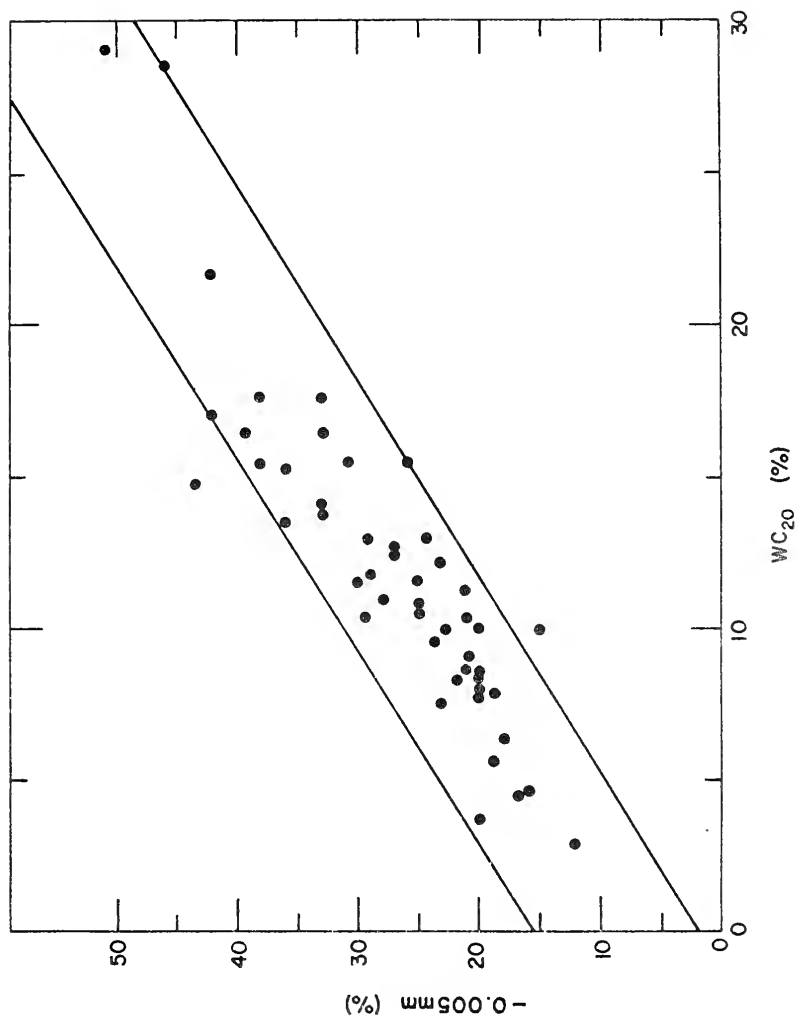


FIGURE F-4 RELATIONSHIP BETWEEN THE PORTION ($-0.005mm$) AND WC_{20}

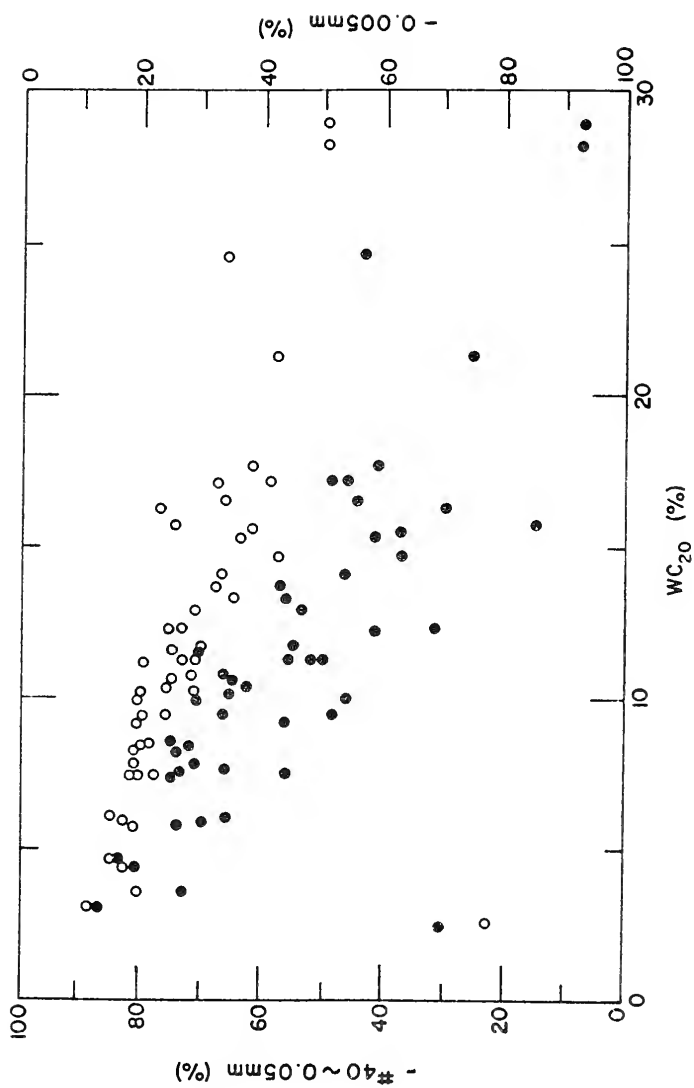


FIGURE F-5 RELATIONSHIP BETWEEN THE PORTION ($- \#40 \sim 0.05mm$ AND $- 0.005mm$) AND WC_{20}

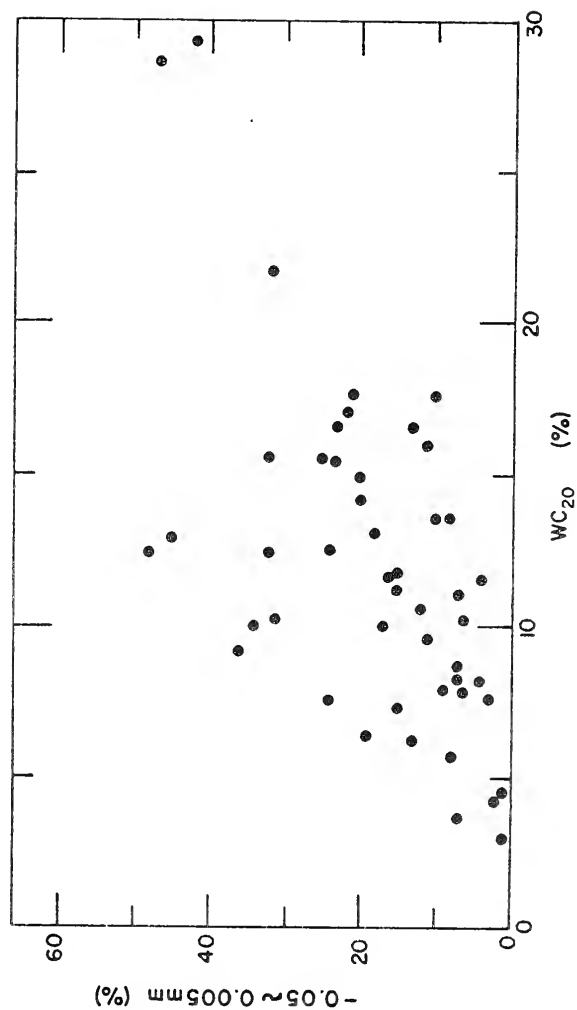


FIGURE F-6 RELATIONSHIP BETWEEN THE PORTION ($-0.05 \text{ mm} \sim 0.005 \text{ mm}$) AND WC_{20}

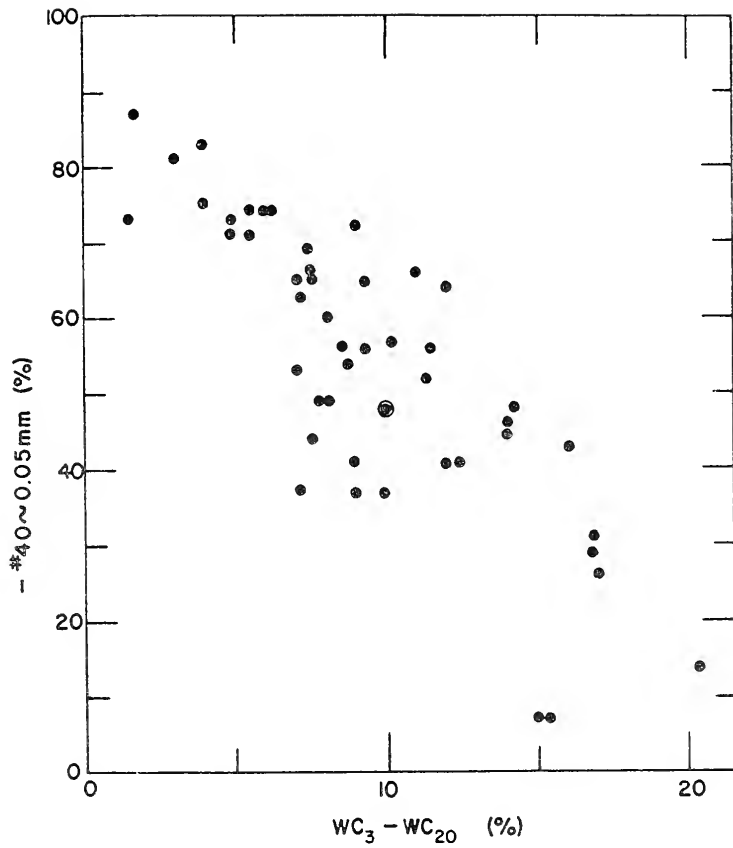


FIGURE F-7 RELATIONSHIP BETWEEN THE PORTION (-#40~0.05mm) AND
(WC₃ - WC₂₀)

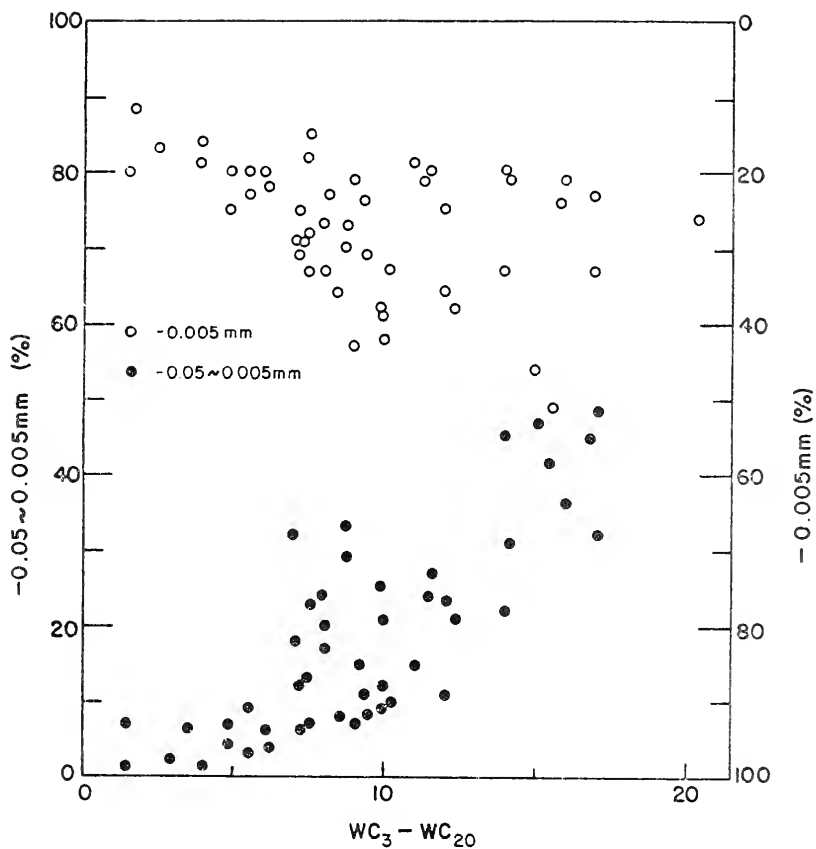


FIGURE F-8 RELATIONSHIP BETWEEN THE PORTION ($-0.05 \sim 0.005 \text{ mm}$ AND -0.005 mm) AND ($WC_3 - WC_{20}$)

